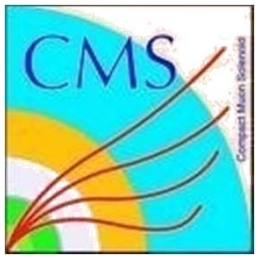
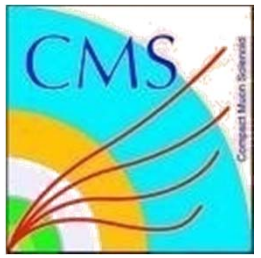




Heavy-ion results from the CMS experiment

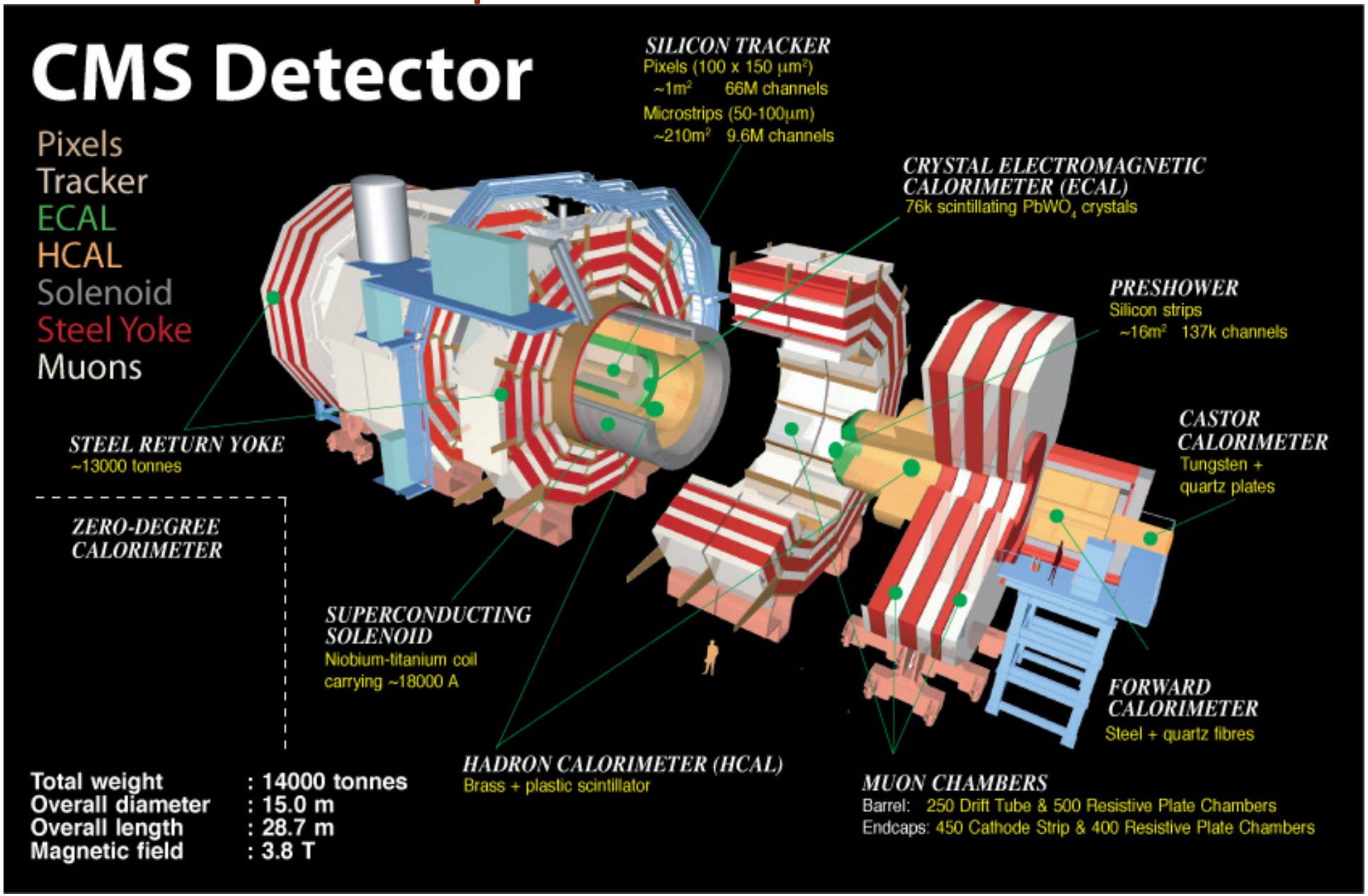
Raphaël Granier de Cassagnac
LLR – École polytechnique / IN2P3
ERC grant "QuarkGluonPlasmaCMS"
on leave at Columbia University

Fermilab, wine and cheese seminar
Batavia, 2012, February 2nd

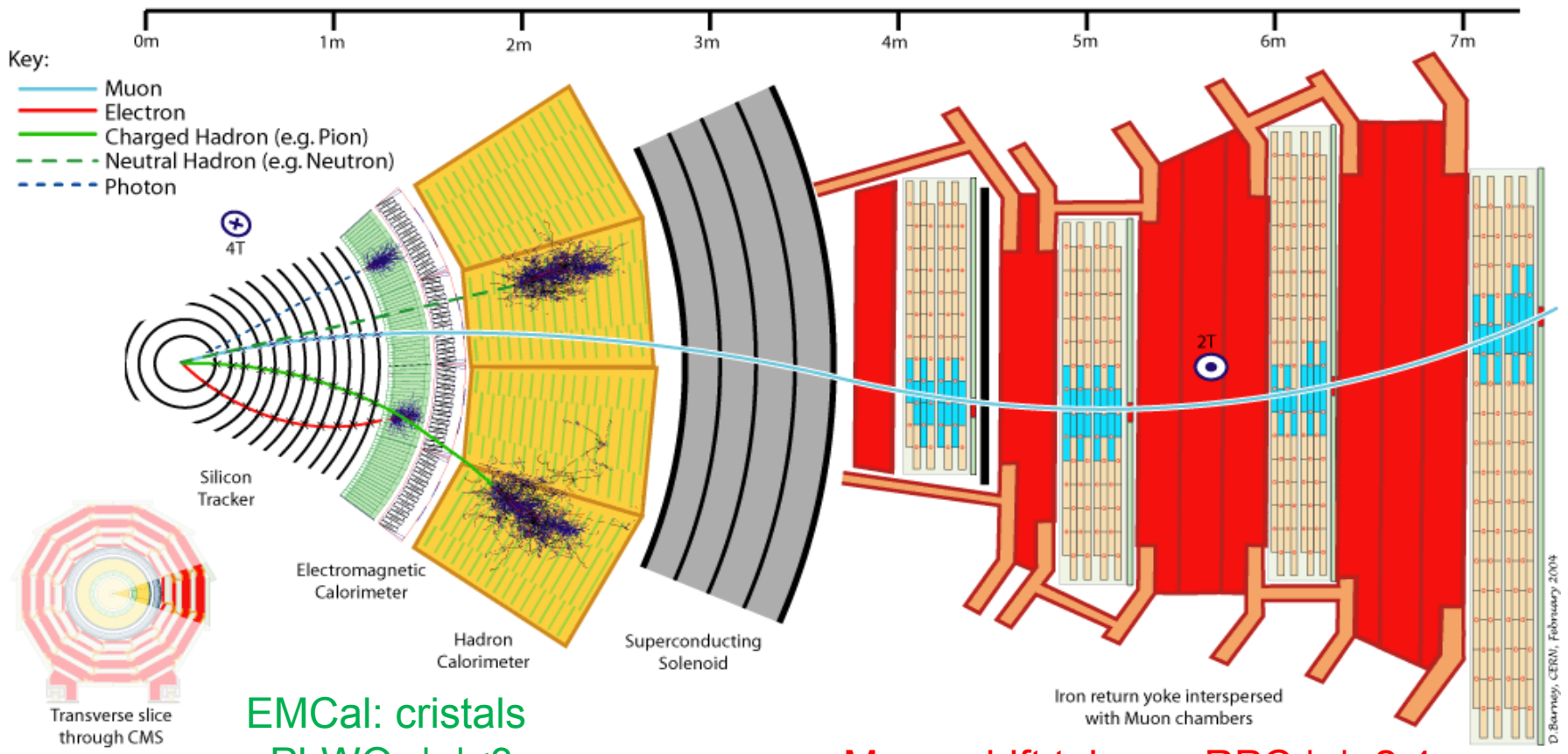
The Quark Gluon Plasma (in brief)

- Hadron deconfinement → Quark+Gluon soup
  - First microseconds after the Big-Bang
  - For $T \gtrsim 150 - 180$ MeV/k_B and $\varepsilon \gtrsim 0.5 - 1$ GeV/fm^3
  - → Heavy-ion collisions
- First hints at SPS (Fixed target, CERN, Geneva)
  - Charmonium suppression
- Extensively produced and studied at RHIC (Collider, BNL, New-York state)
  - From 2000 on, still running, up to $\sqrt{s_{NN}} = 200$ GeV
  - Jet quenching, elliptic flow, thermal photons, charmonia…
- Now at LHC, new regime (√sx14) and new probes:
  - Reconstructed jets, Z and W, photons, Upsilons… for which CMS is well adapted

Compact Muon Solenoid



Particle detection (|η|<2.4)



EMCal: cristals
$PbWO_4$ |η|<3

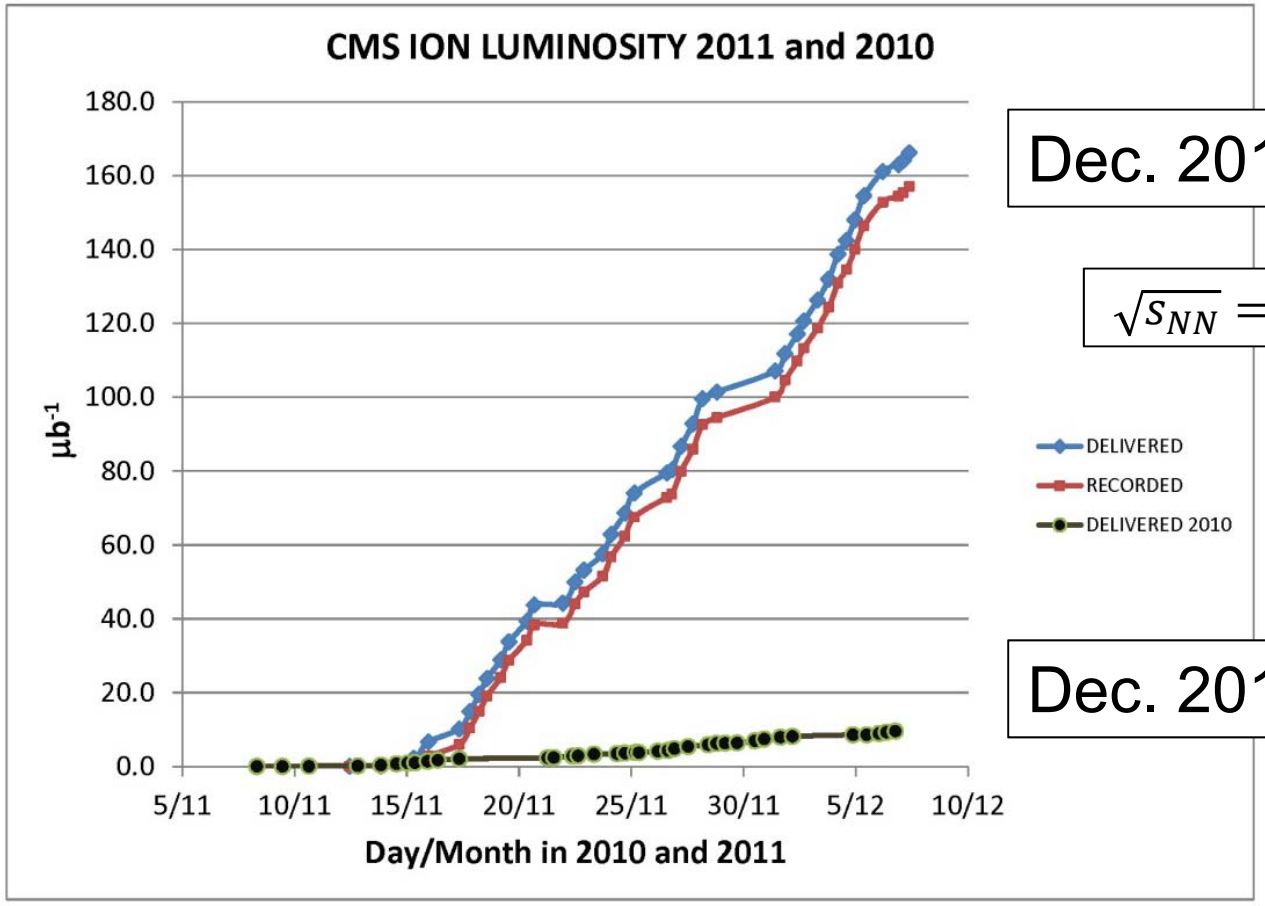
Muon: drift tubes + RPC |η|<2.4

Silicium: pixels (3) and strips (10) |η|<2.4

HCal: Scintillation
|η|<5

+ Higher pseudo-rapidity calorimetry extension

PbPb collisions at the LHC



Dec. 2011: ≈ 160 μb^{-1}

$\sqrt{s_{NN}} = 2.76$ TeV

Dec. 2010: ≈ 7 μb^{-1}

+ Mar. 2011: ≈ 230 nb^{-1} pp at 2.76 TeV
  - Equivalent statistics for hard (rare) probes to the 2010 PbPb run

Comprehensive list of topics

- Multiplicity and transverse energy
  - $dN_{ch}/d\eta \approx 1600$ and $dE_T/d\eta \approx 2$ TeV !
- Particle correlations
  - Elliptic flow and higher harmonics
  - Di-hadron correlations (the "ridge")
- Standard candles: Electro+Weak bosons
  - Isolated photons
  - $Z \rightarrow \mu\mu$ (signal for $Z \rightarrow ee$)
  - $W \rightarrow \mu\nu$
- Quarkonium suppression
  - J/ψ, prompt and non-prompt
  - Y ground and excited states
- Jet quenching
  - High p_T particle suppression, incl. 2011 data!
  - Di-jet imbalance*
  - Fragmentation functions

JHEP08 (2011) 141
HIN-11-003

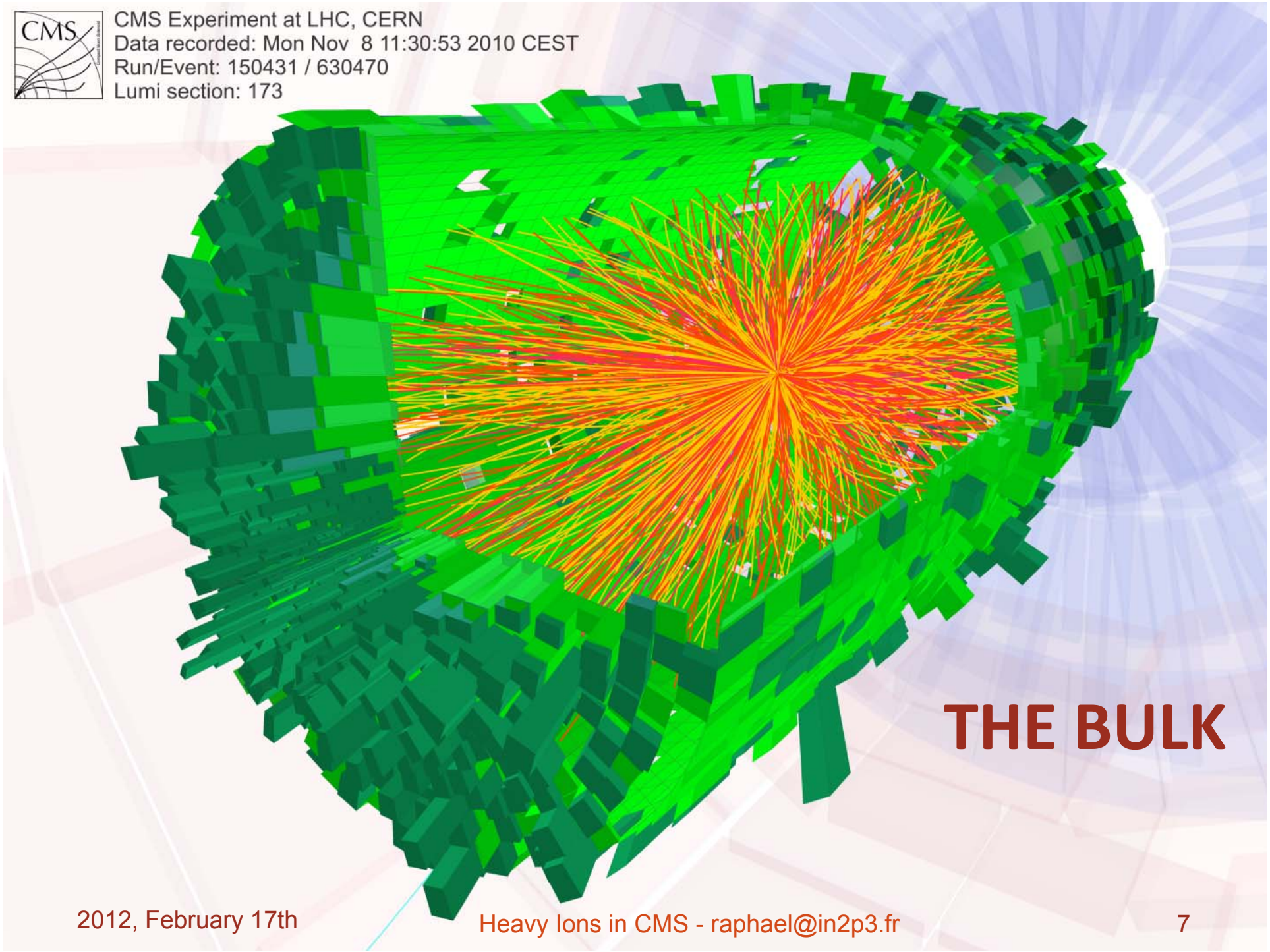
HIN-10-002 & 11-005
JHEP07 (2011) 076
arXiv: 1201.3158

arXiv: 1201.3158
PRL106 (2011) 212301
New preliminary result

arXiv:1201.5069
PRL107 (2011) 212301

arXiv:1202.2554
PRC84 (2011) 024906
HIN-11-004

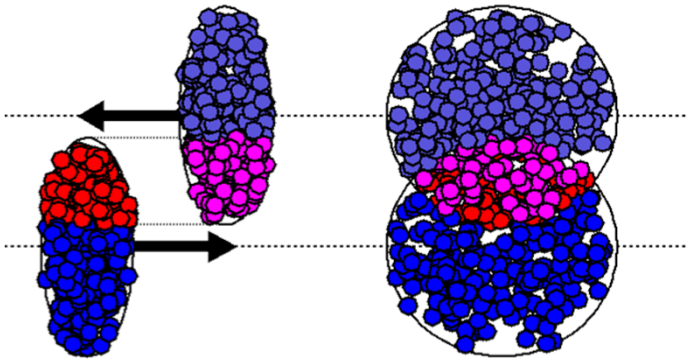
* Ed. Wenger, FNAL semniar, Jan 28th 2011

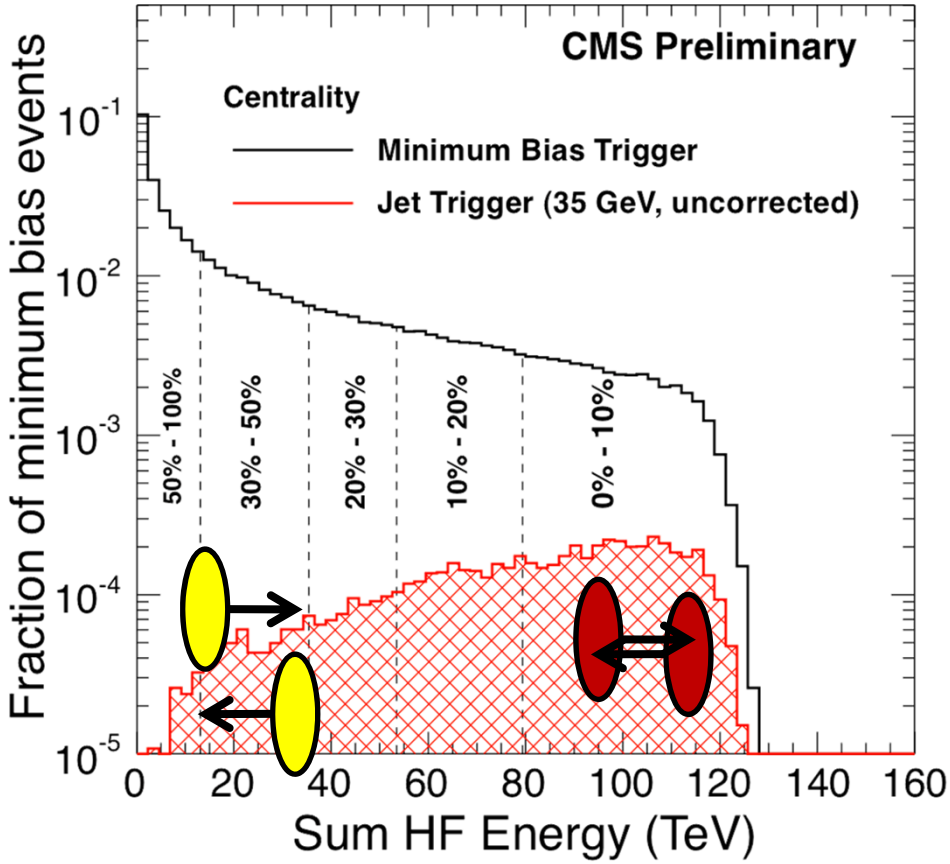

CMS Experiment at LHC, CERN
Data recorded: Mon Nov 8 11:30:53 2010 CEST
Run/Event: 150431 / 630470
Lumi section: 173
THE BULK


the HULK!
TM

Centrality definition

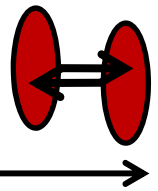
- Collision centrality related to energy deposit in (forward) calorimeters
- Then to geometrical quantities:
  - N_{part} = number of participating nucleons

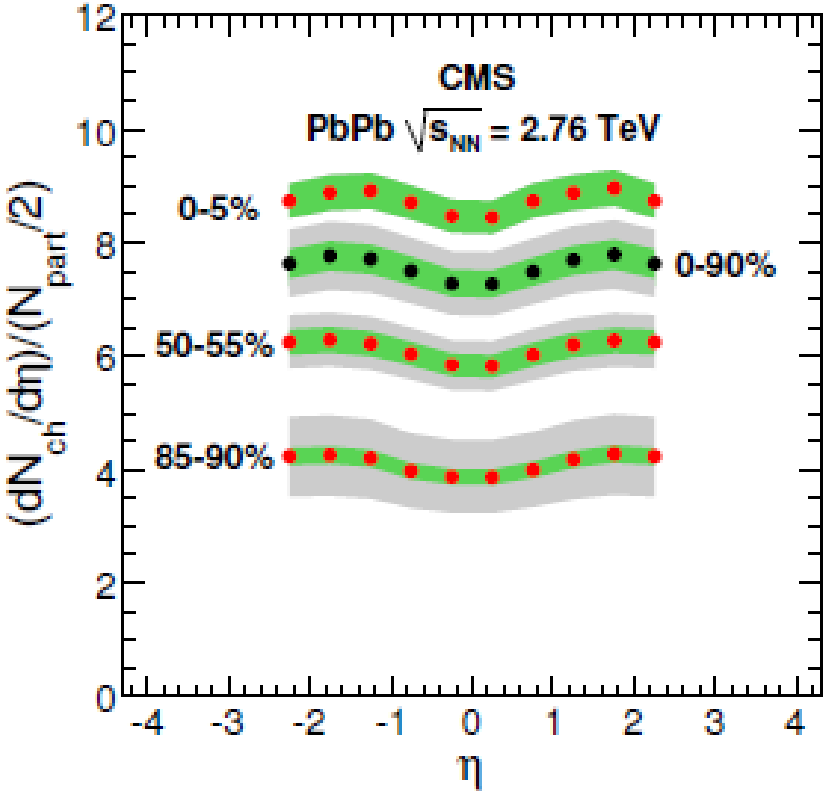


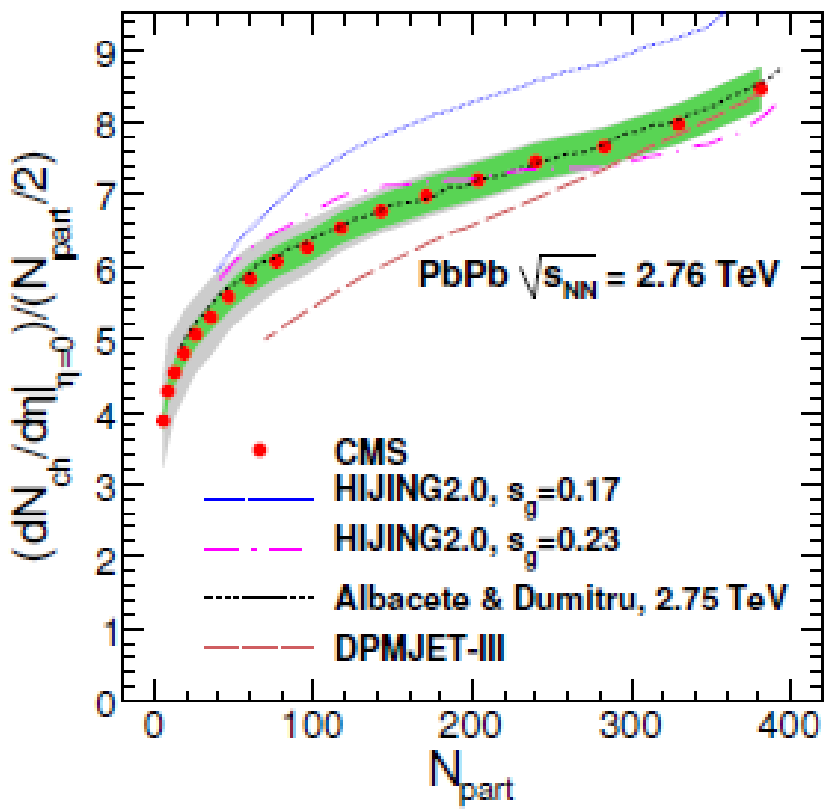


JHEP08 (2011) 141

Total multiplicity

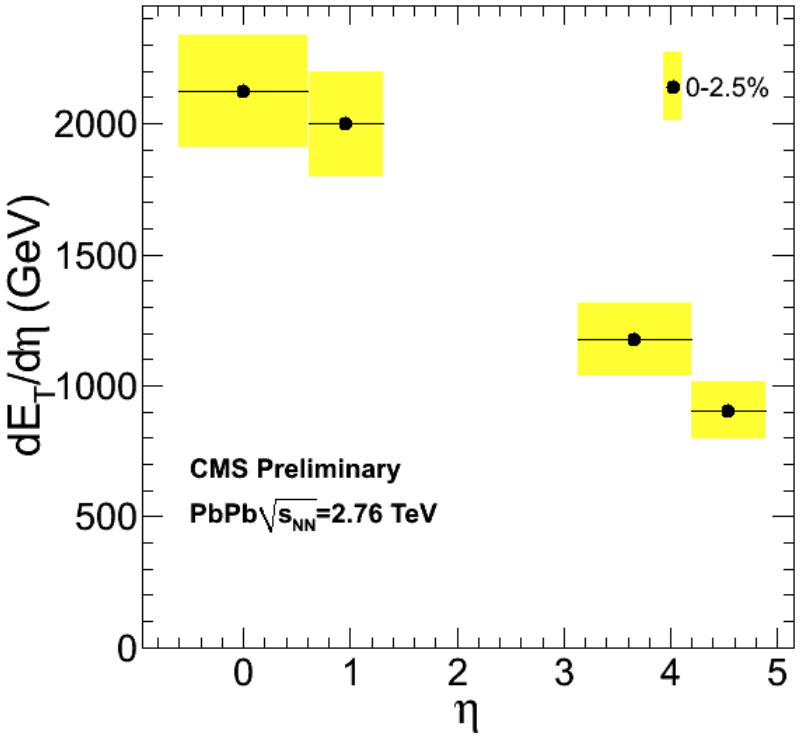


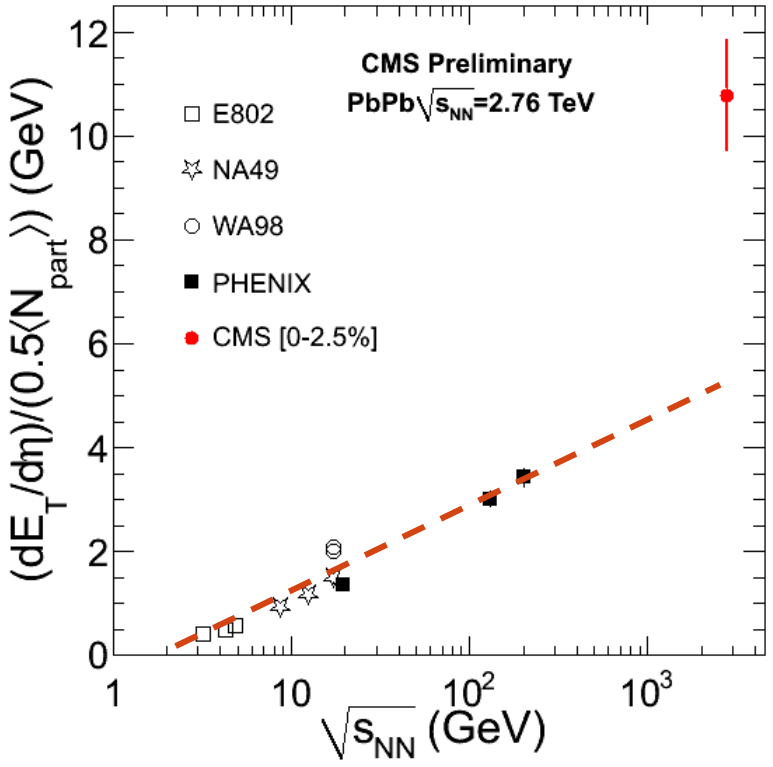




- About 1600 charged particles per pseudorapidity unit
- Centrality dependence providing inputs to (initial state) models

Total transverse energy





- 2 TeV per units of pseudorapidity
- Wide range of pseudorapidity
- 3 times larger than RHIC = 100 times nuclear density

CMS-PAS-HIN-11-003

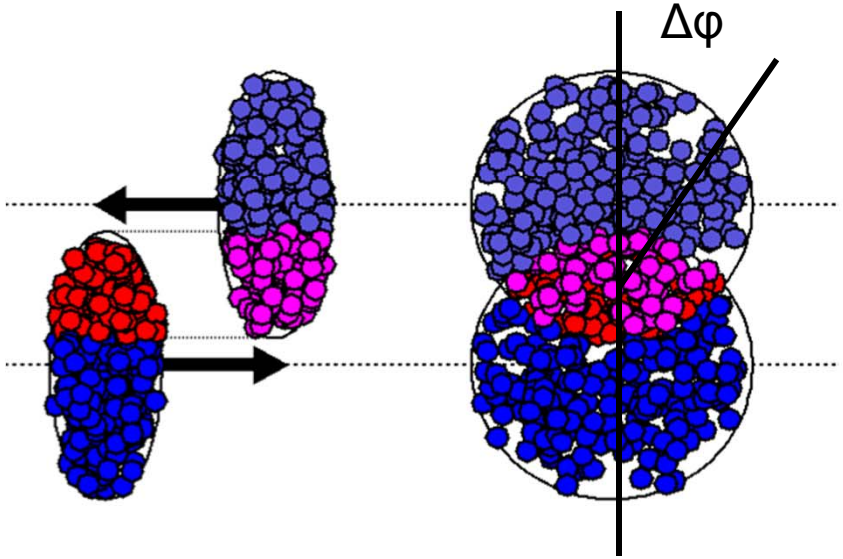
Elliptic flow

CMS-PAS-HIN-10-002

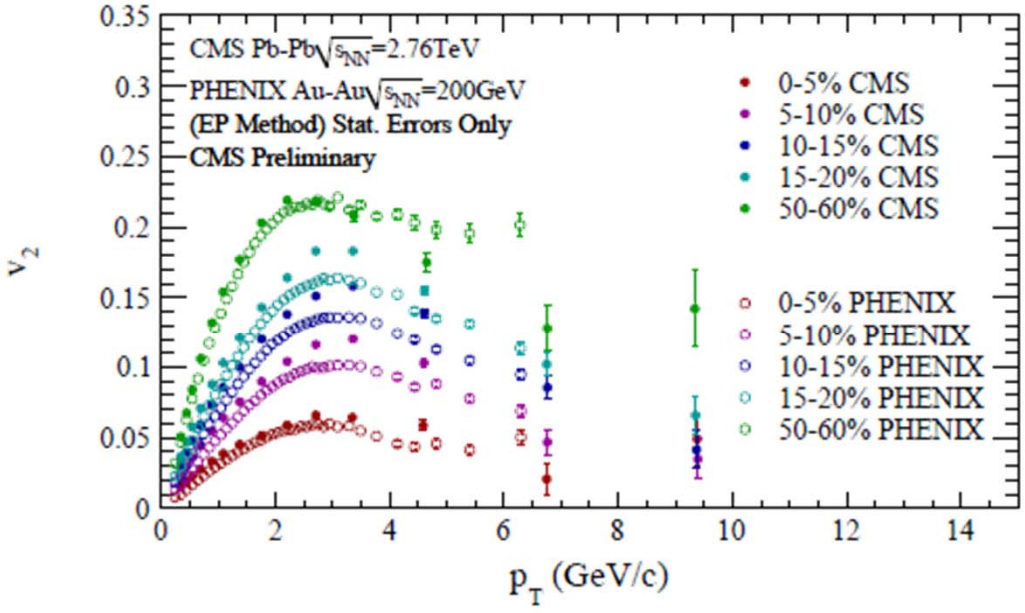
- In mid-central collisions, almond-shaped overlapping region

→ Pressure gradient

→ Azimuthal anisotropy



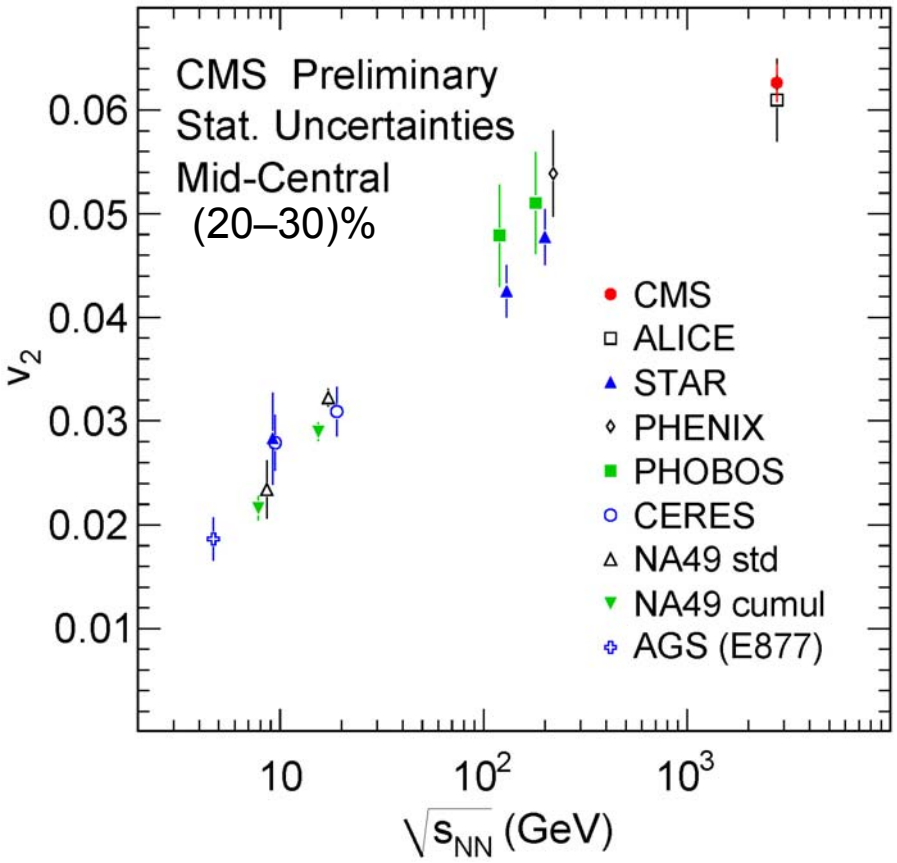
- v_2 = 2nd Fourier coefficient of the azimuthal distribution of particles wrt reaction plane (Δφ)

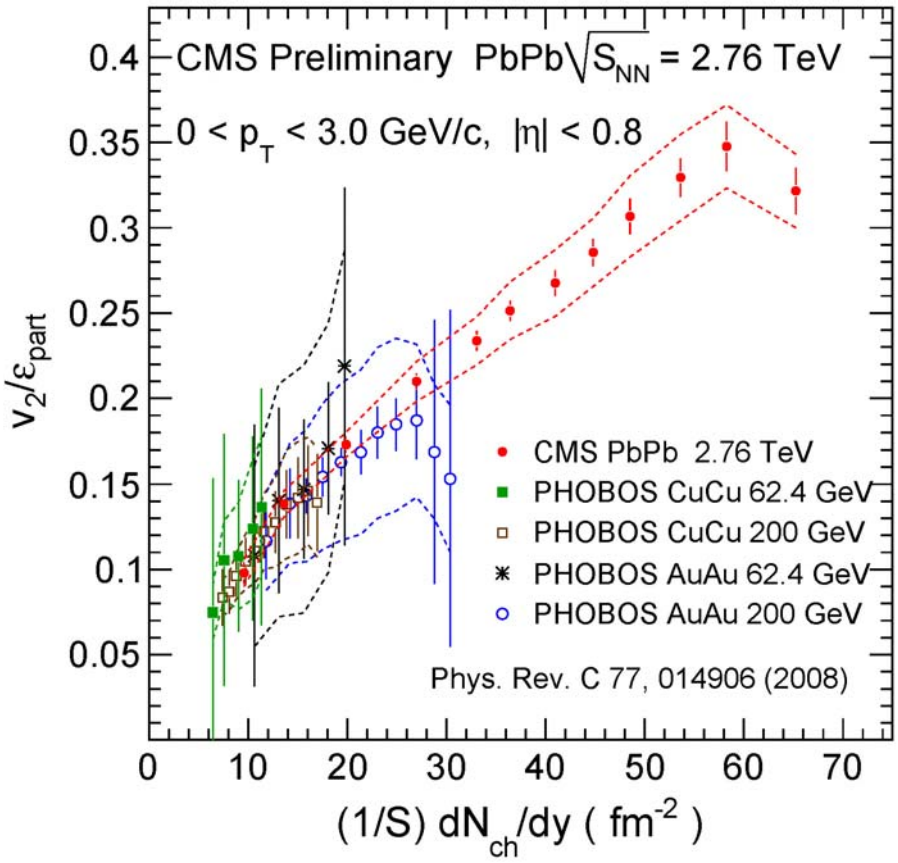


- Similar to RHIC…

Elliptic flow

CMS-PAS-HIN-10-002



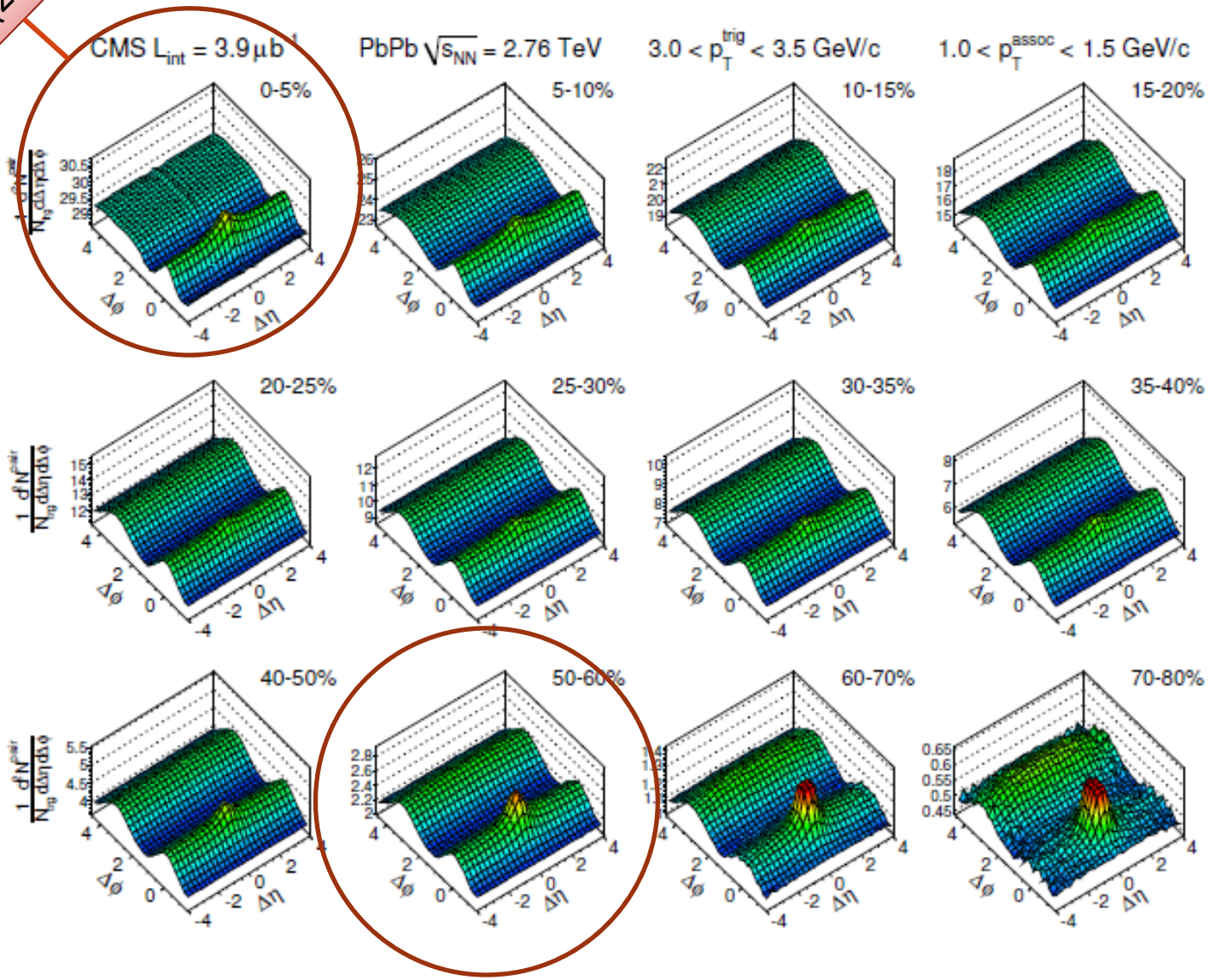


- Modest raise wrt to lower energy experiments
- Participant eccentricity scaling with transverse density

Dihadron correlations

JHEP07 (2011) 076

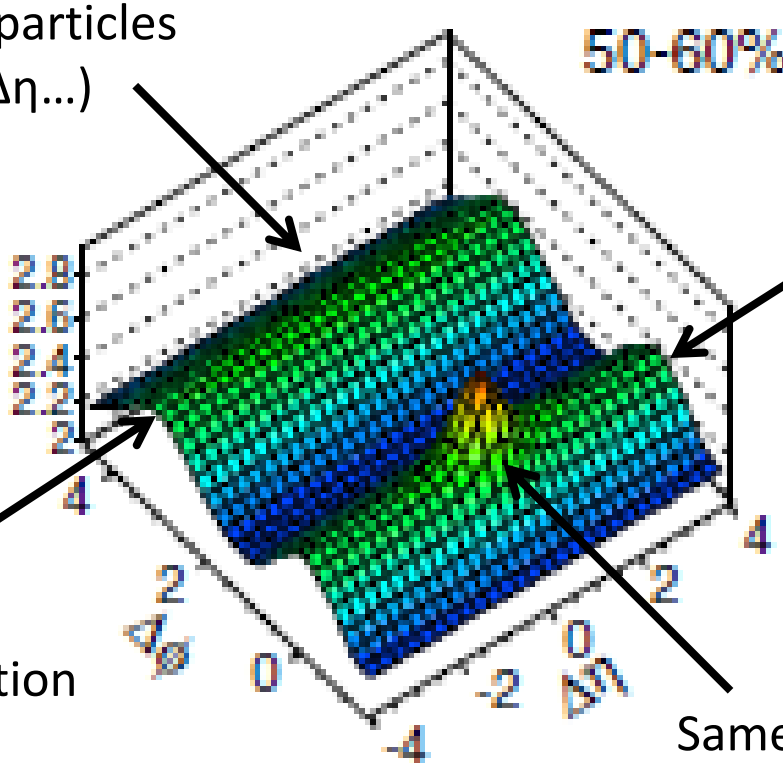
arXiv: 1201.3158



Dihadron correlation

Zooming in…

Opposite-jet particles
(Δϕ ≈ π, Δη…)

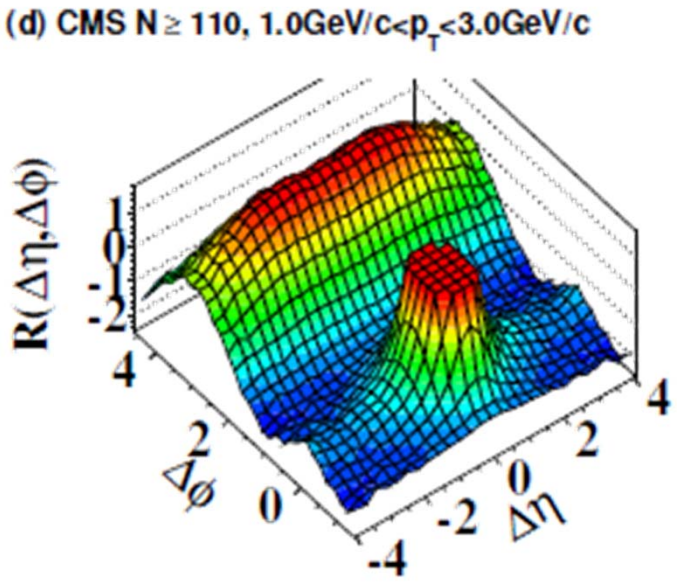


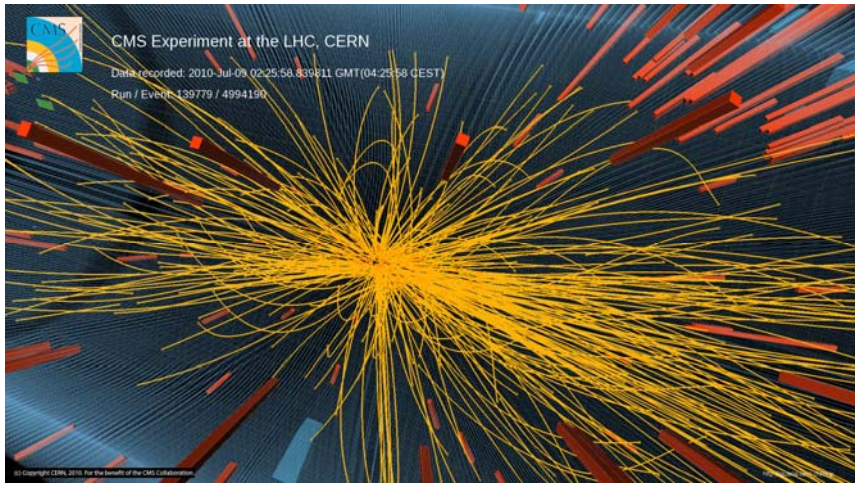
Long-range correlations
(Δϕ ≈ 0, Δη up to 4)
The “ridge” already
seen at RHIC…

Elliptic flow,
cos 2Δϕ modulation

Same-jet particles
(Δϕ ≈ 0, Δη ≈ 0)

Back to proton-proton





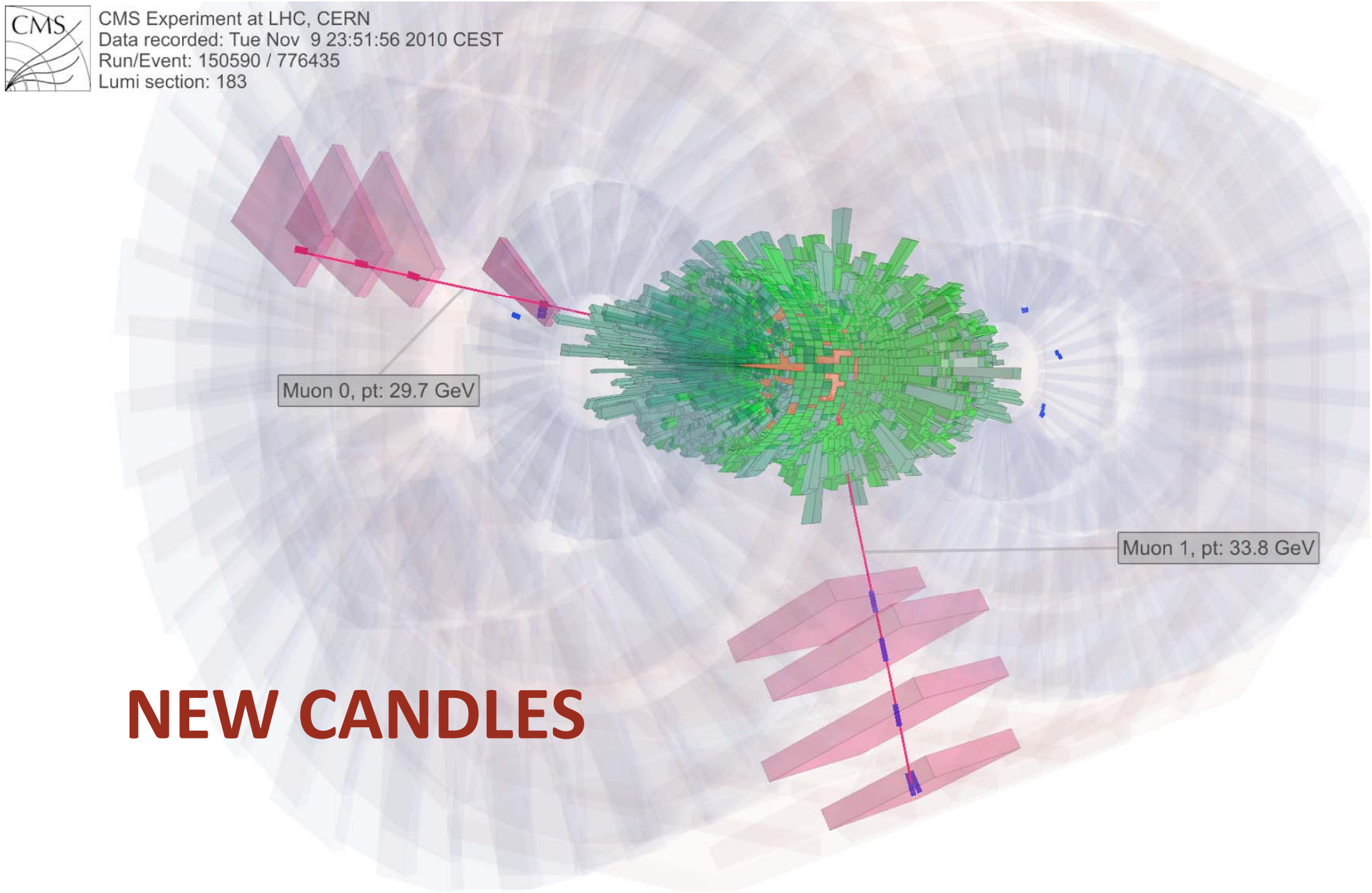
- Ridge also seen in pp high-multiplicity events
  - Heavy-ion like effect in a pp event
  - But interpretation is not easy
  - Look for other heavy-ion like effects?

JHEP09 (2010) 091

Conclusion 1: bulk and correlations

- In the line of RHIC results, particle correlations studies brings a lot of information
- No dramatic surprises wrt RHIC
  - The fluid is still perfect
- Interpretations underway…
  - In arxiv:1201.3158, the "ridge" in PbPb is well reproduced by factorizing single particle azimuthal harmonics and could just reflect collective motion (v_2) and overlap-region fluctuations (v_n)…

Much more details in arXiv:1201.3158
See also HIN-11-005

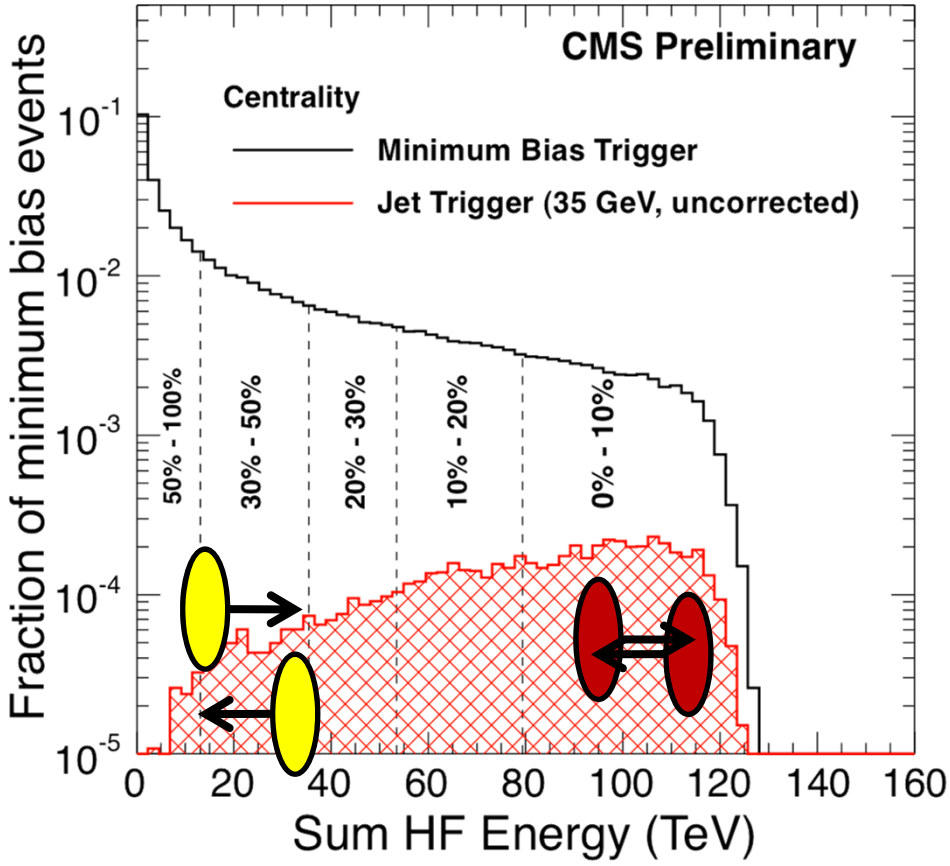


NEW CANDLES

Electro+Weak bosons should go through the colored medium without feeling it

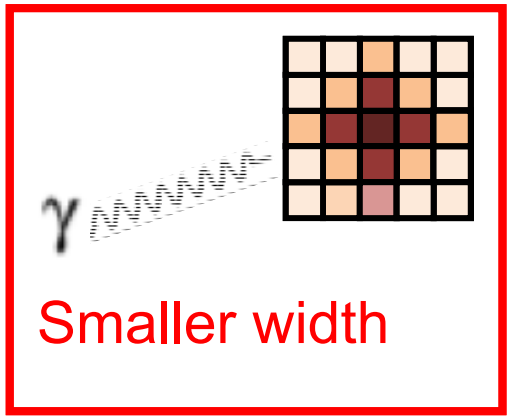
Back to centrality

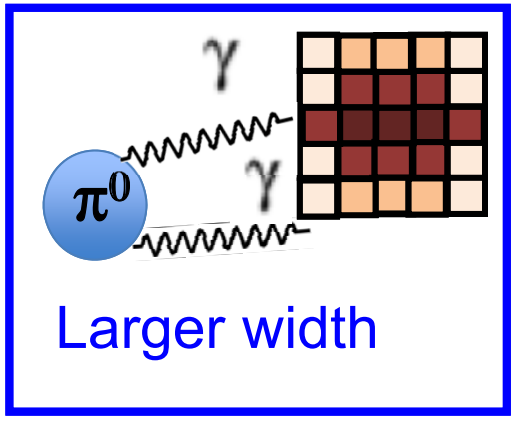
- Collision centrality related to energy deposit in (forward) calorimeters
- Then to geometrical quantities:
  - N_{coll} = number of elementary NN collisions
- Hard probes are supposed to scale with N_{coll}, in the absence of medium effect, $R_{AA} = 1$ →

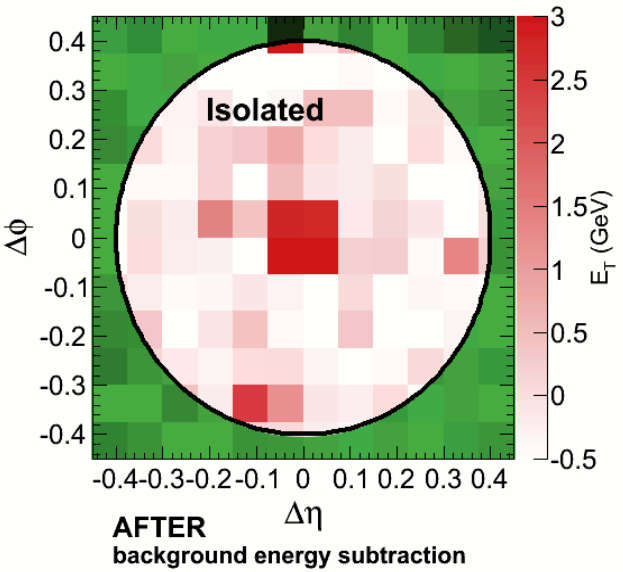


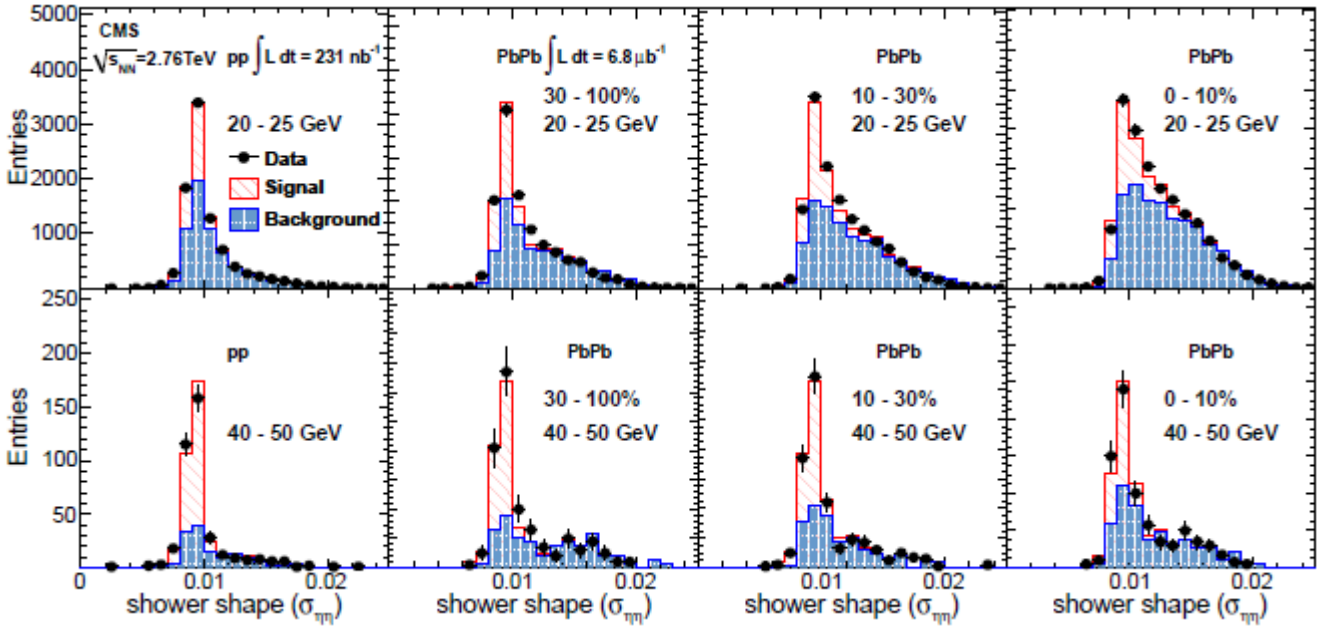
$$R_{AA} = \frac{dN^{AA}}{dN^{PP} \times \langle N_{coll} \rangle}$$

Isolated photons





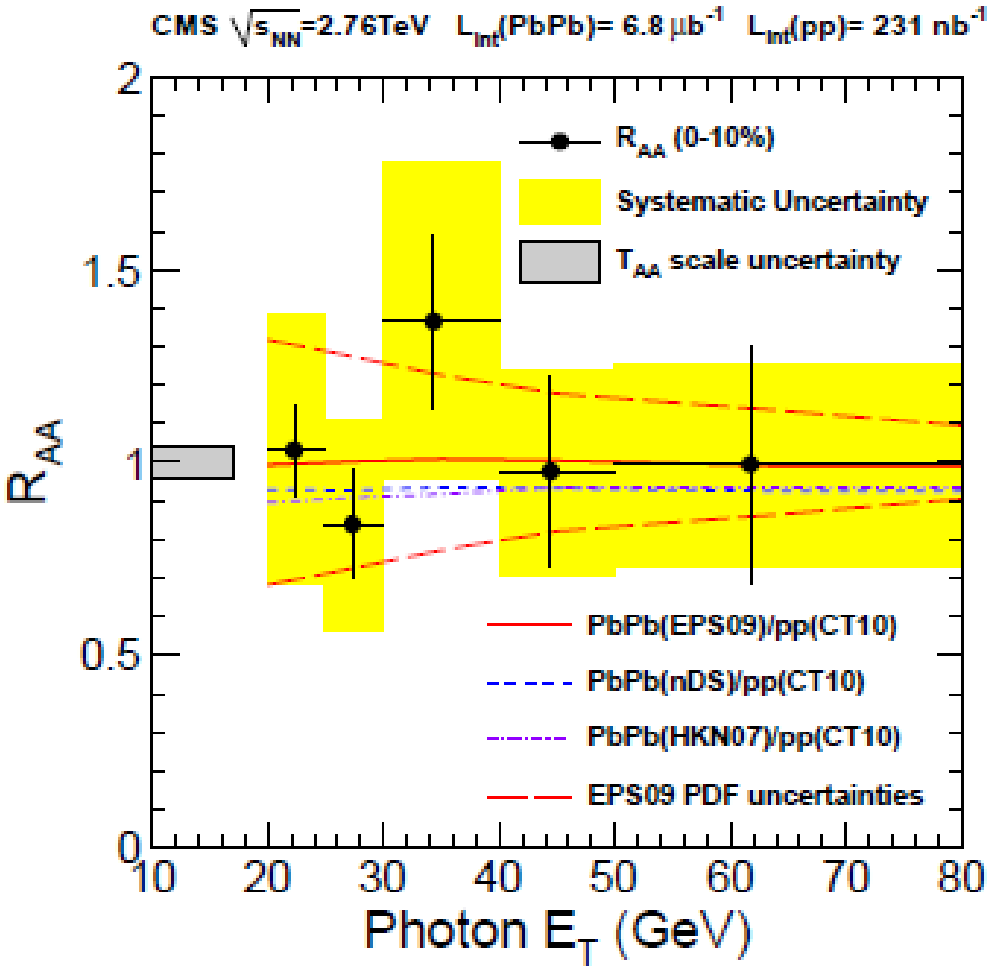




arXiv:1201.3093

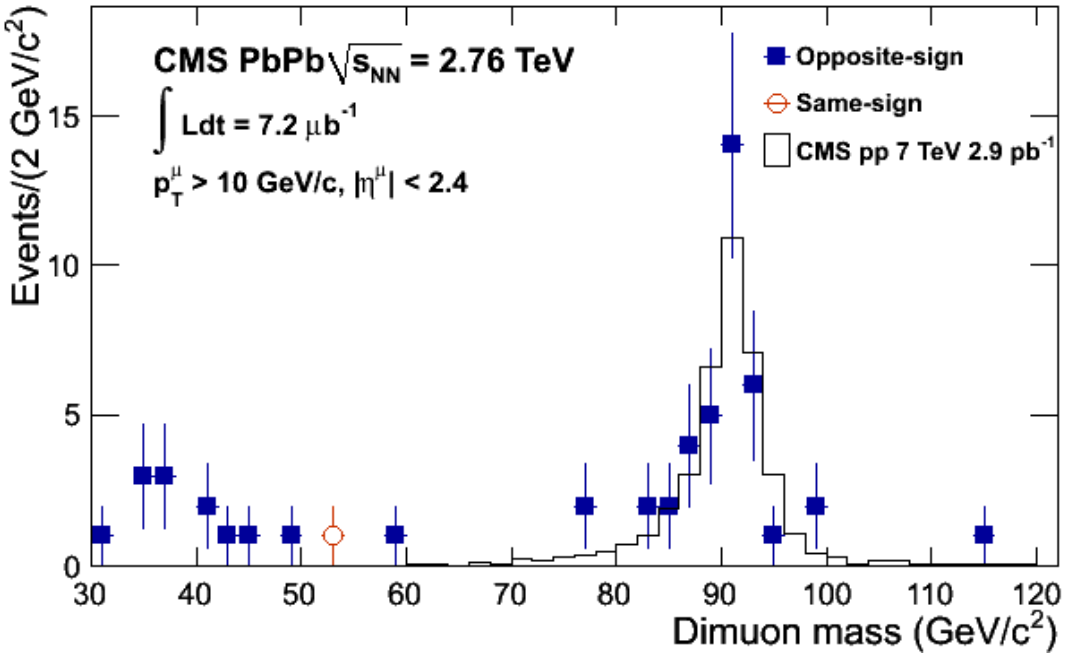
Isolated photons

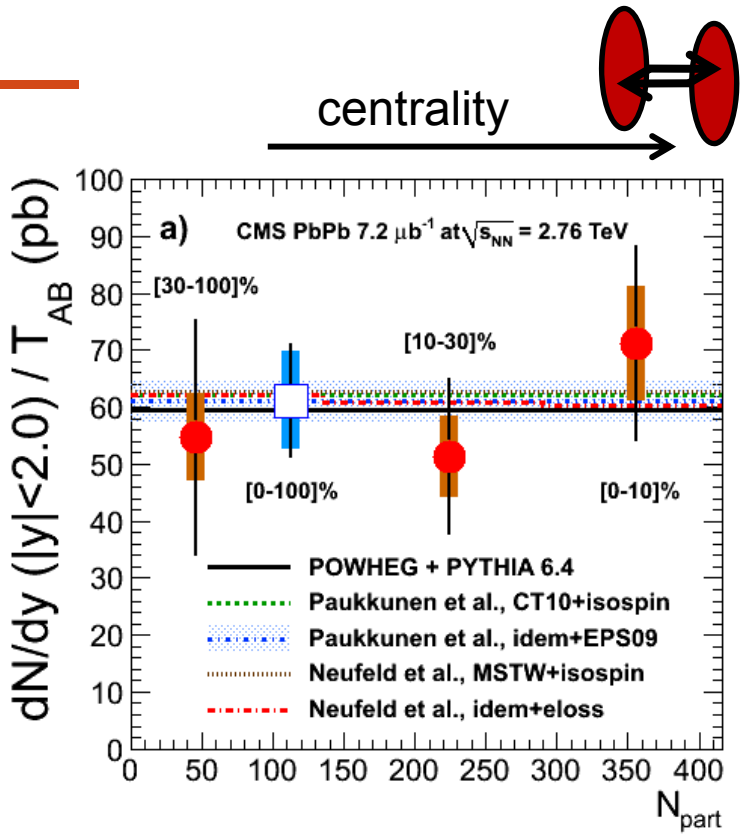
- Photons are unmodified
  - 20-30% uncertainty, mostly due to background
- Here for the 10% most central collisions
  - But also for all centrality
- Not precise enough (yet) to constrain nuclear pdfs



arXiv:1201.3093

Z bosons

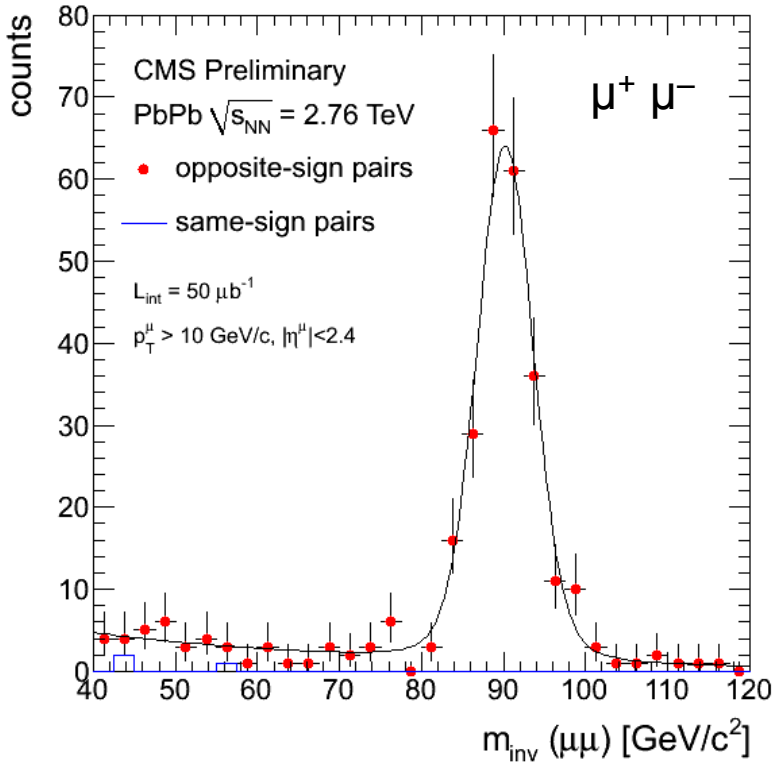


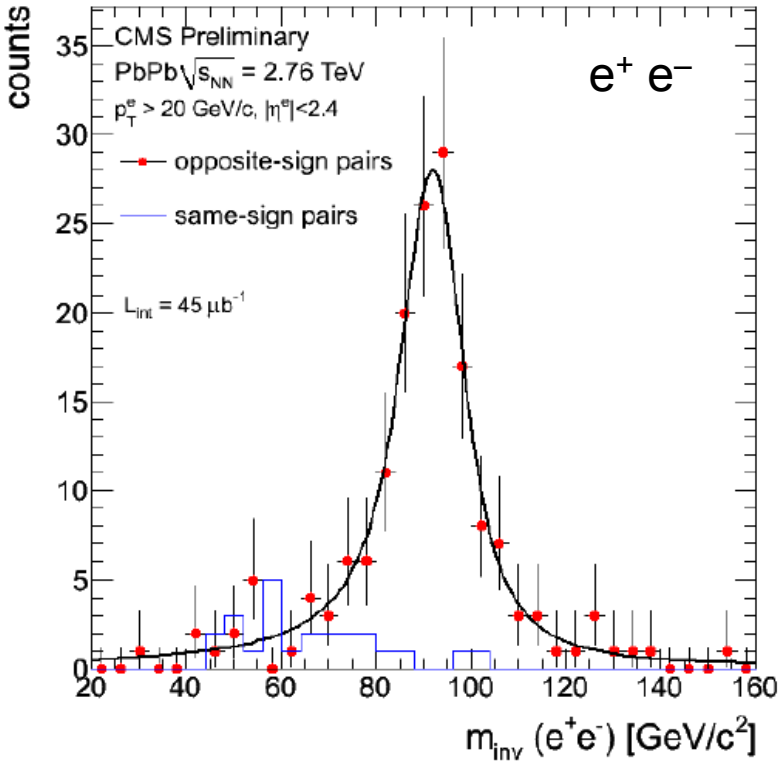


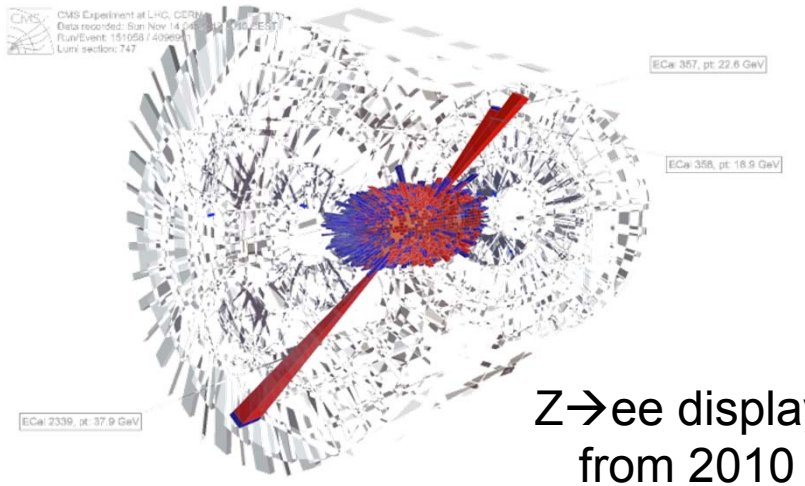
- 39 counts over a negligible background
- No R_{AA} here, but direct comparison to solid theory: no modifications

PRL106 (2011) 212301

A quick look at Z's from (a third of) 2011 data



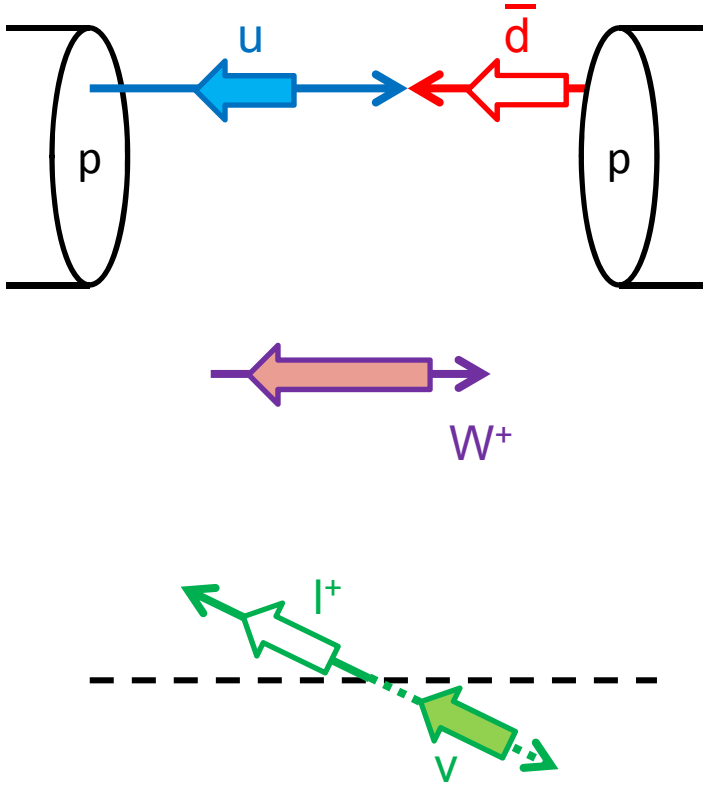




Z→ee display from 2010

W bosons

- At LO, W bosons are produced by fusion of a valence quark and an antiquark from the sea: $u\bar{d} \rightarrow W^+$ and $\bar{u}d \rightarrow W^-$
  - Strong isospin effect since Pb has higher d/u than proton
    - Cancels for $W^+ + W^-$
  - Also a strong acceptance difference (not heavy-ion specific)

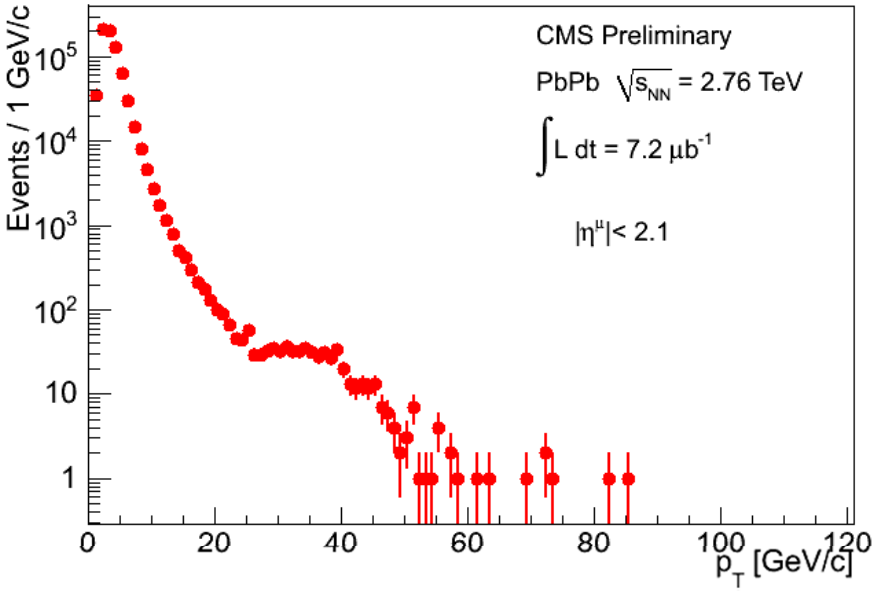


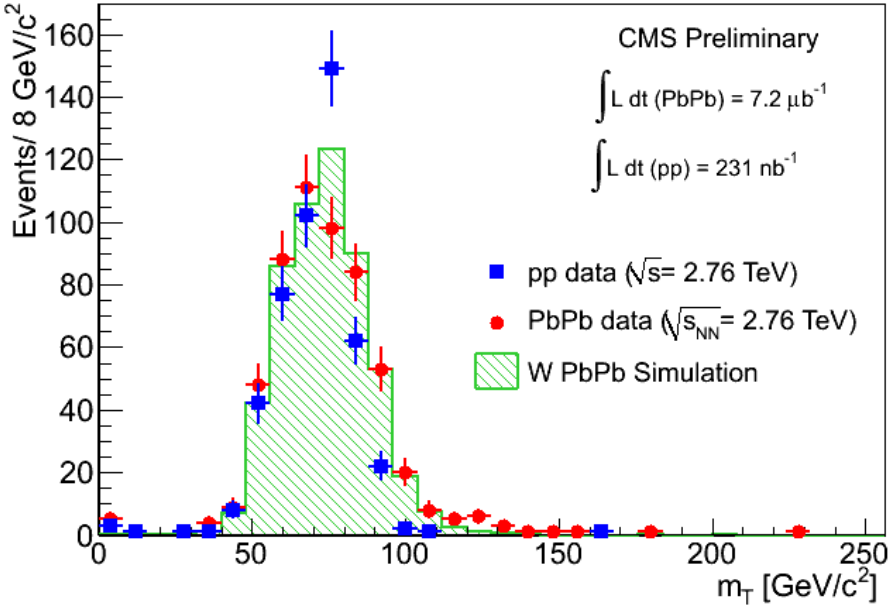
B. de la Cruz, Feb. 2012, Santiago de Compostela
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN11008

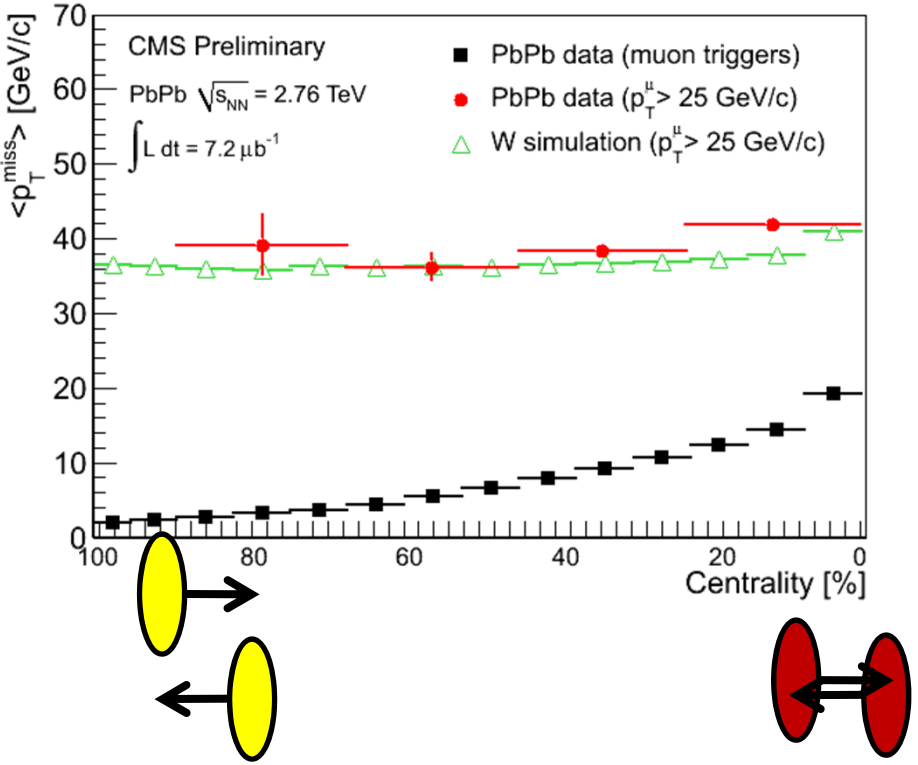
NEW

W bosons

- Signal already visible in muon p_T spectrum →
- Build up simple missing p_T from tracks ↘
- Then transverse mass ↓



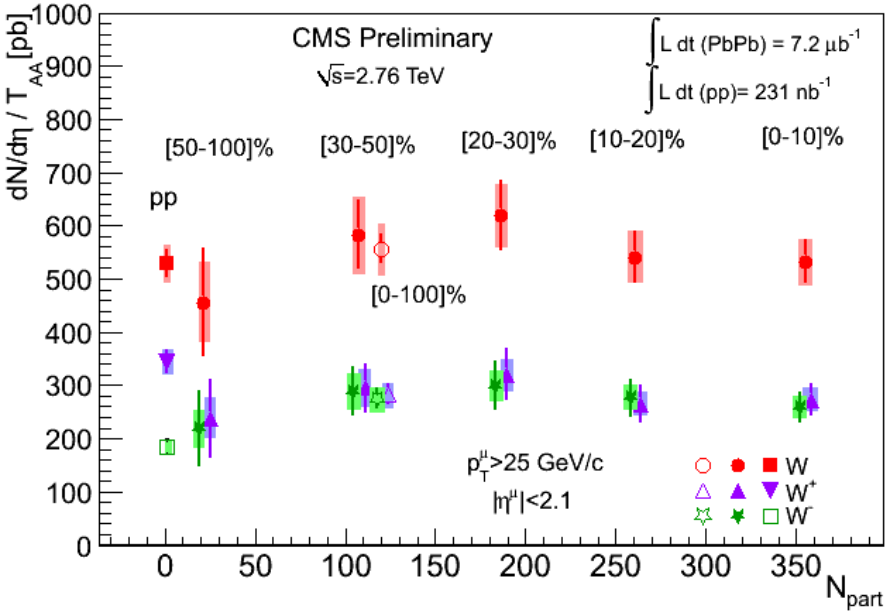


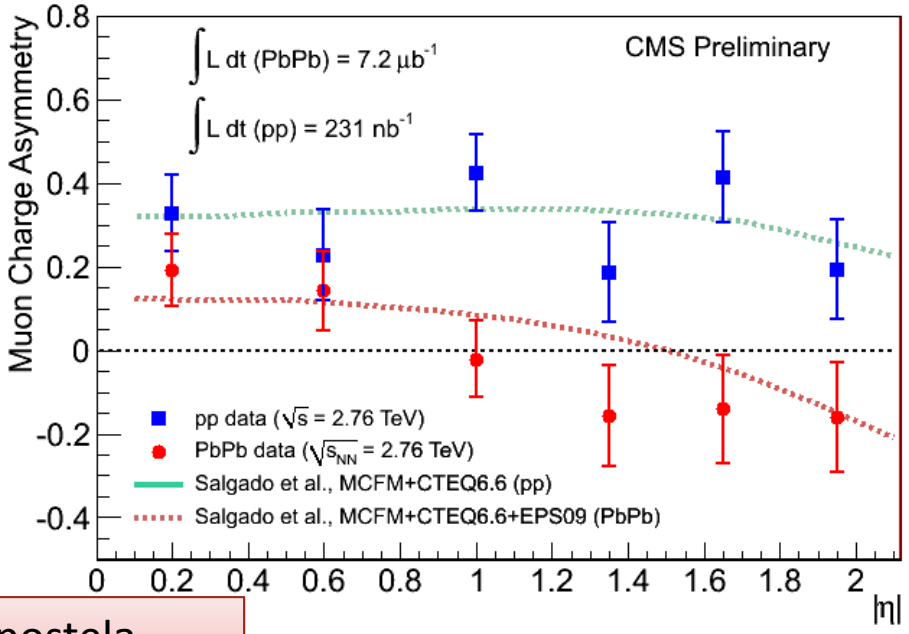


NEW

W bosons

- No centrality dependence
  - $R_{AA}(W^+) \approx 0.7$
  - $R_{AA}(W^-) \approx 1.3$
  - $R_{AA}(W) = 1.04 \pm 0.07 \pm 0.12$
- Muon charge asymmetry
  - $(W^+ - W^-) / (W^+ + W^-)$
  - Also matching predictions

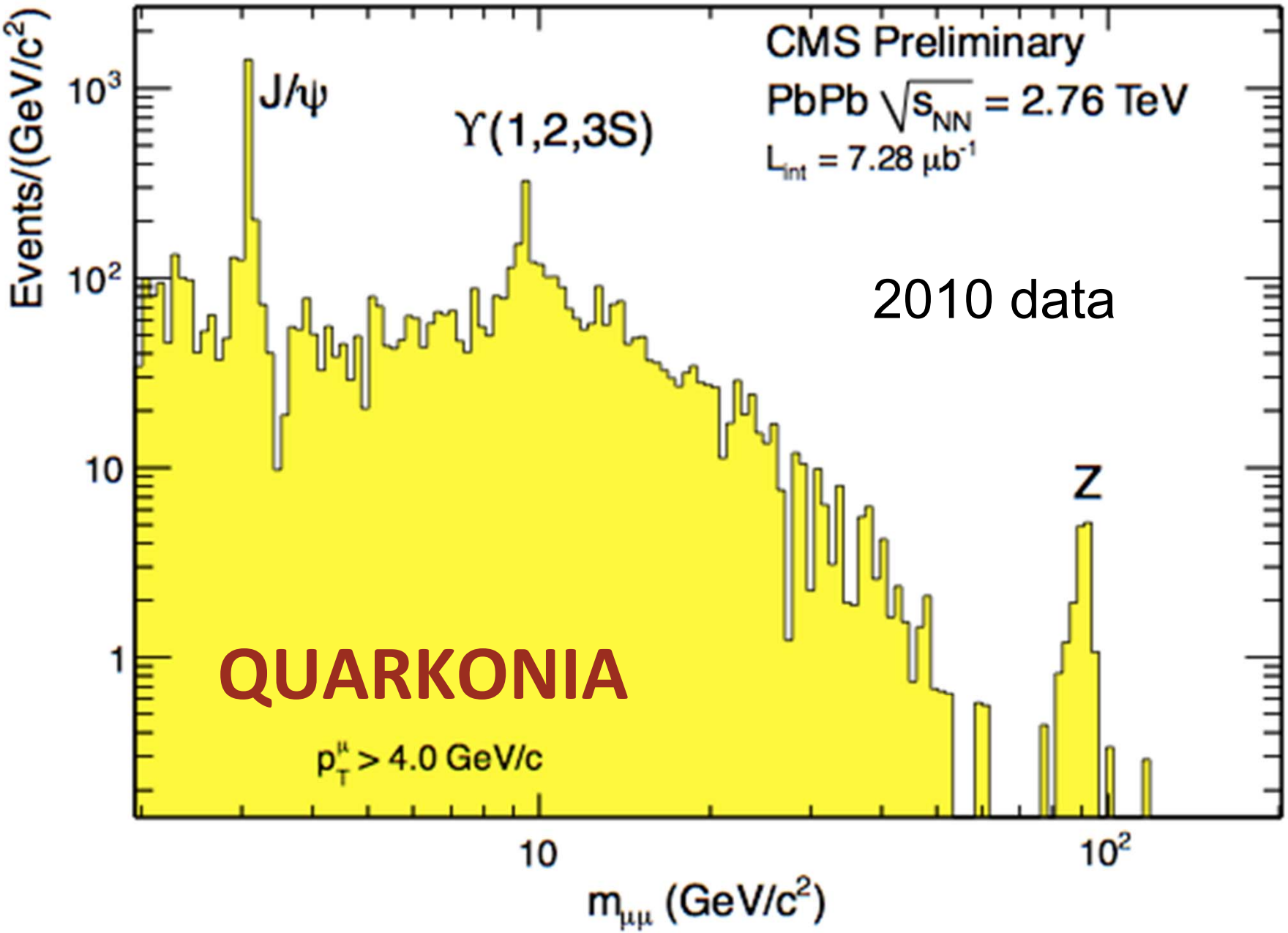


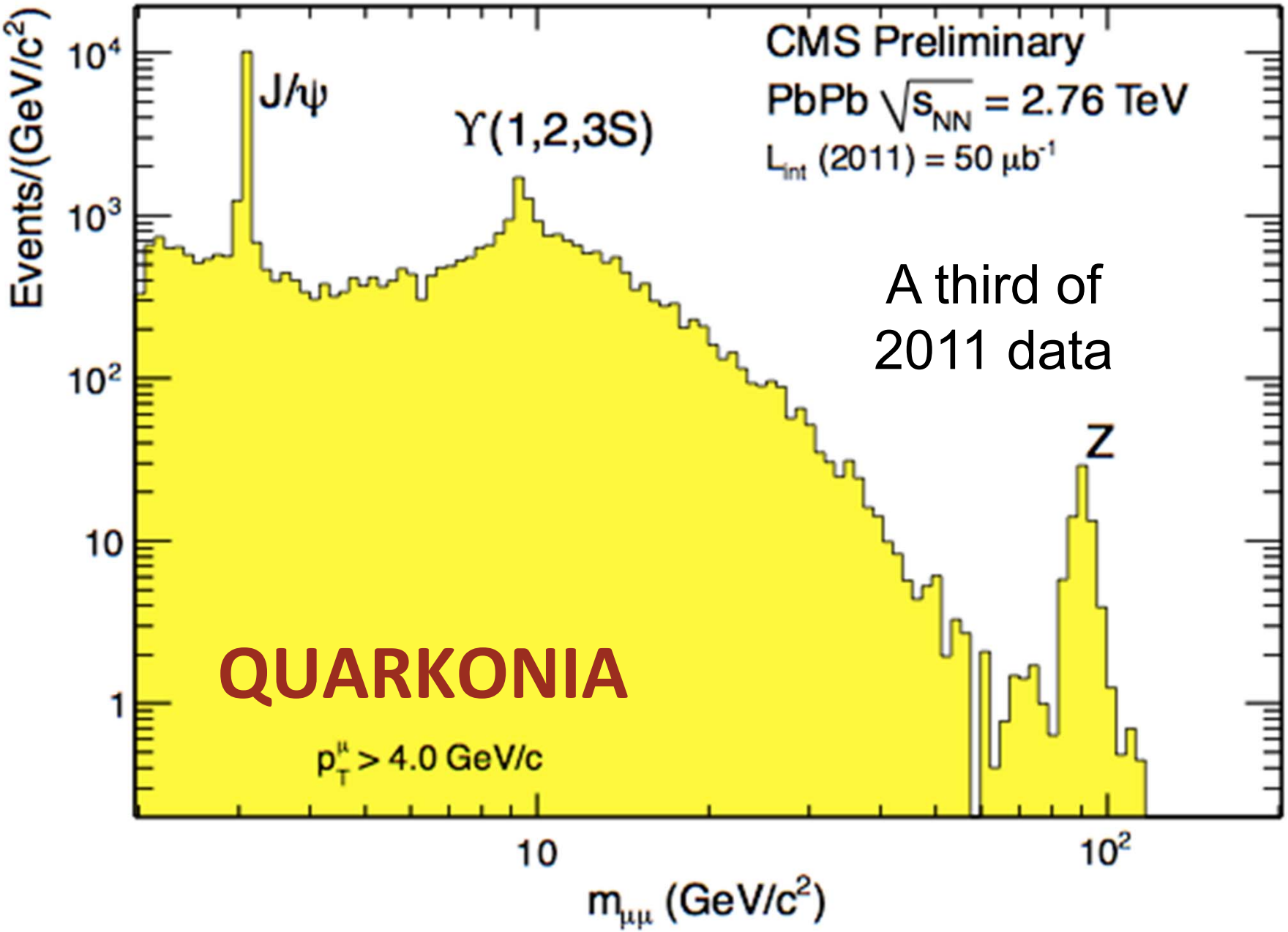


B. de la Cruz, Feb. 2012, Santiago de Compostela
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN11008

Conclusion 2: electro+weak bosons

- Photons, Z and W are unmodified
- More precise measurements (analyses of the 2011 run) should start constraining the nuclear pdfs
- First step toward γ-jet and Z-jet measurements
  - Photons and Z acting as in-situ calibrators of the opposite jet…


CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
L_{int} = 7.28 μb^{-1}
J/ψ
Υ(1,2,3S)
Z
2010 data
QUARKONIA
p_T^μ > 4.0 GeV/c
Events/(GeV/c^2)
$m_{\mu\mu}$ (GeV/c^2)
10^3
10^2
10
1
10
10^2

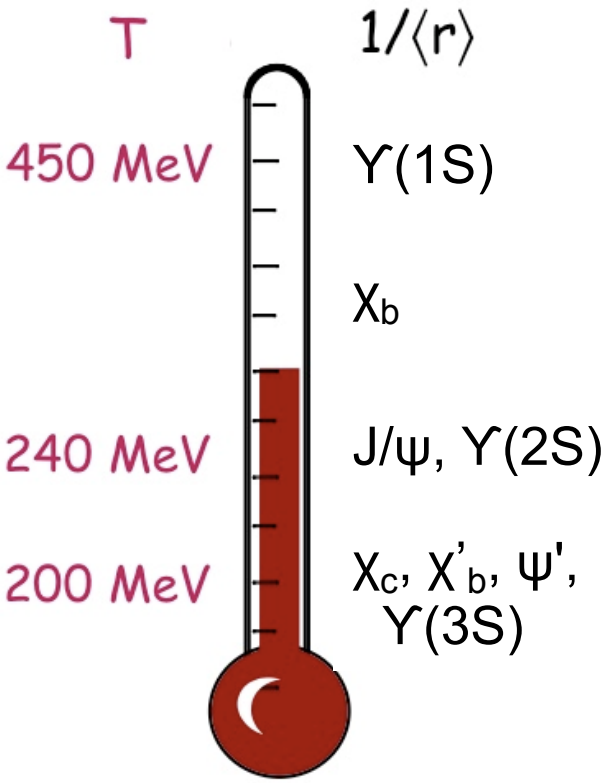

CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
L_{int} (2011) = 50 μb^{-1}
J/ψ
Υ(1,2,3S)
Z
A third of
2011 data
QUARKONIA
$p_T^\mu > 4.0$ GeV/c
Events/(GeV/c²)
$m_{\mu\mu}$ (GeV/c²)
10⁴
10³
10²
10
1
10
10²

Quarkonium suppression

- Old predicted signature of the QGP
  - Quarkonia should melt one after the other, depending on their binding energy
  - Recent example of melting temperatures →

- @ SPS / RHIC, no / marginal access to the (yet unresolved) Upsilon family
- @ SPS, J/ψ and ψ' studied in detail
- @ RHIC, J/ψ brought up two surprises…

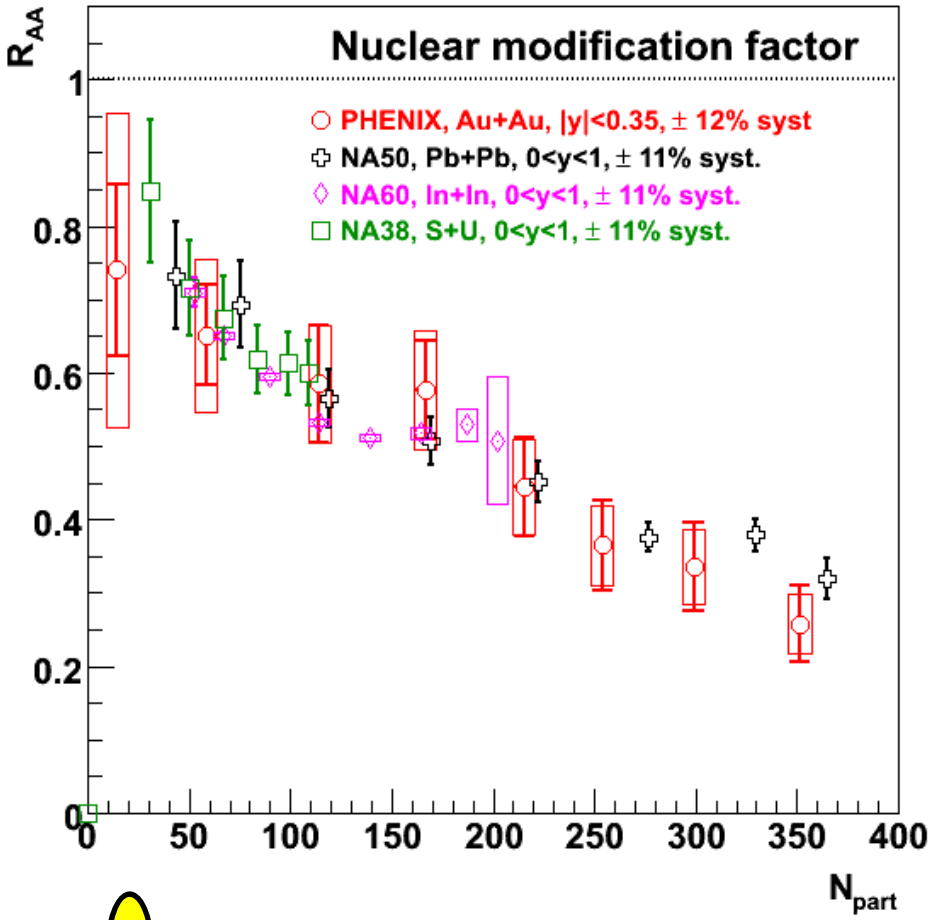
Matsui & Satz, PLB168 (1986) 415

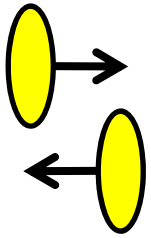


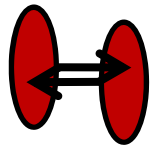
Mocsy, EPJC61 (2009) 705
BNL workshop in June

J/ψ at RHIC (all p_T)

- Two surprises:
  - At midrapidity, same suppression **at RHIC** and **at SPS**, while density must be higher



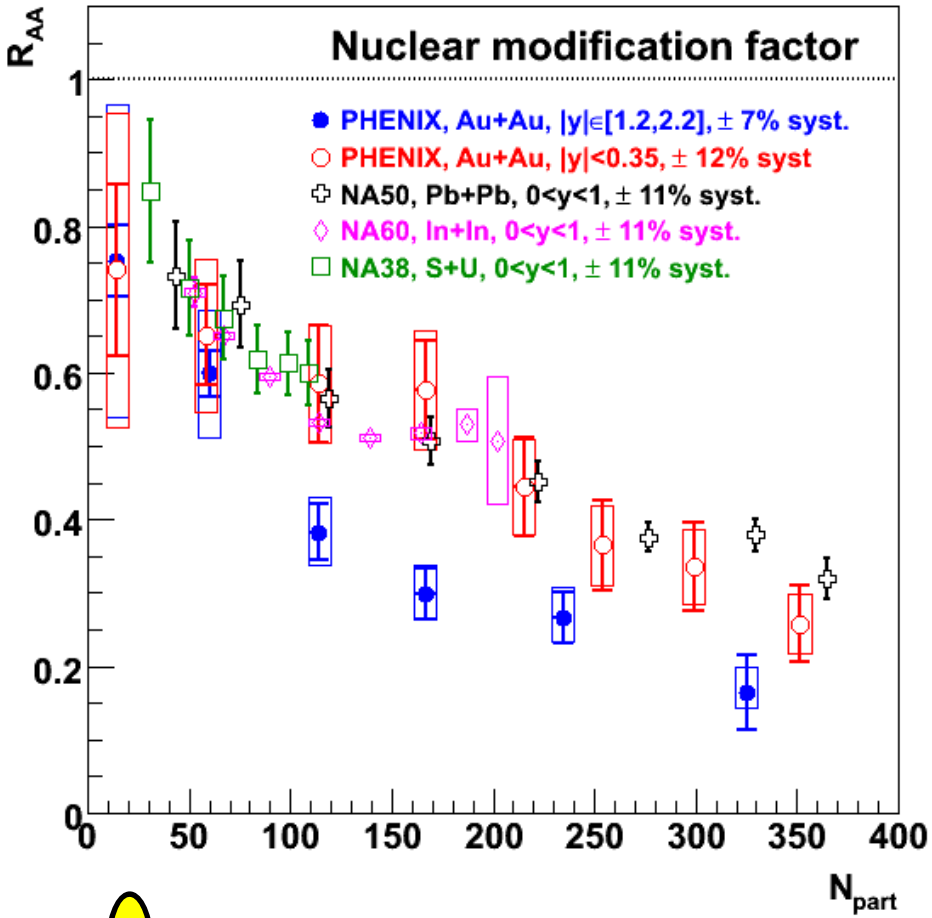


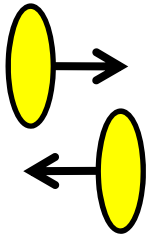


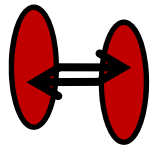
PHENIX, PRL98 (2007) 232301, also 1103.6269
SPS from Scomparin @ QM06

J/ψ at RHIC (all p_T)

- Two surprises:
  - At midrapidity, same suppression **at RHIC** and **at SPS**, while density must be higher
  - More suppression **at forward rapidity** at RHIC, while density must be lower
- Two popular answers:
  - Cold: shadowing / saturation brings forward yields down
  - Hot: recombination of uncorrelated $c\bar{c}$ brings midrapidity yield up

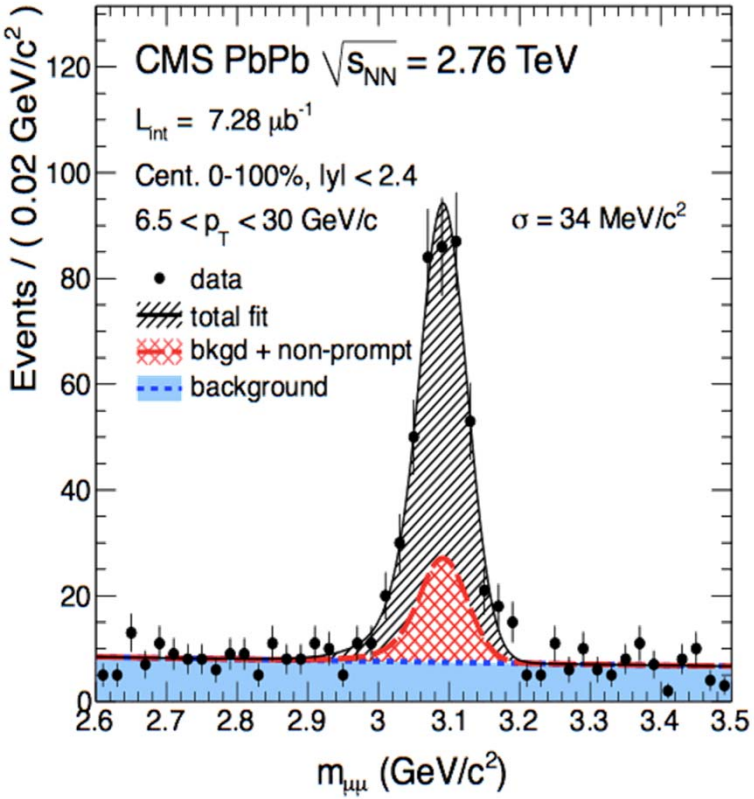


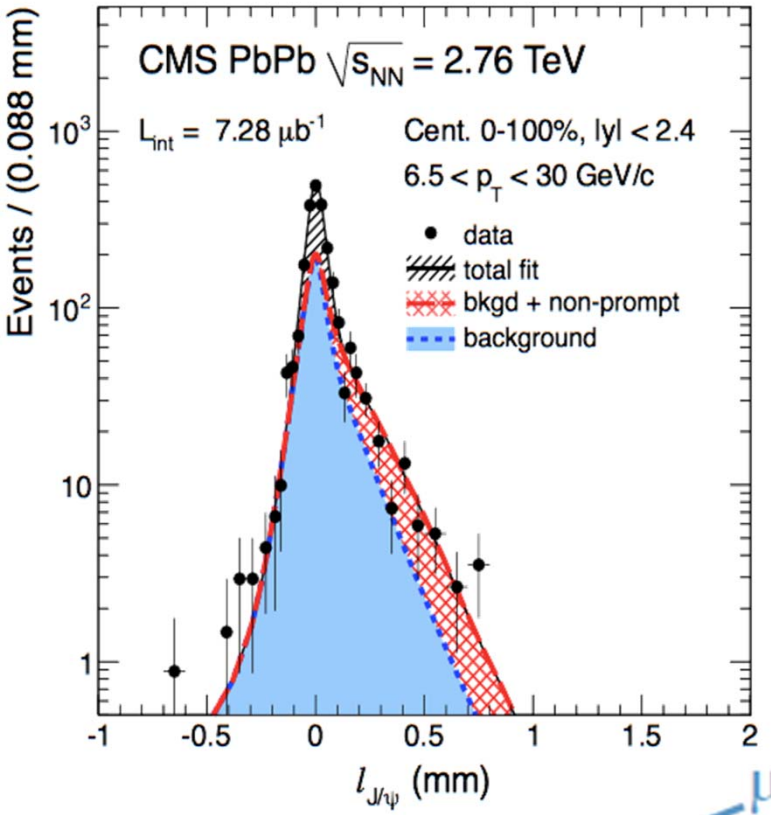


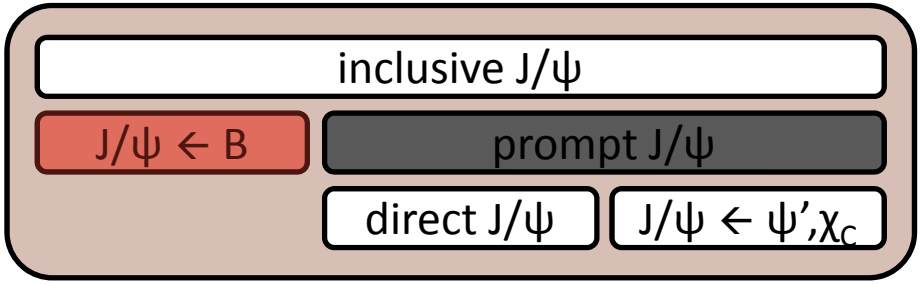


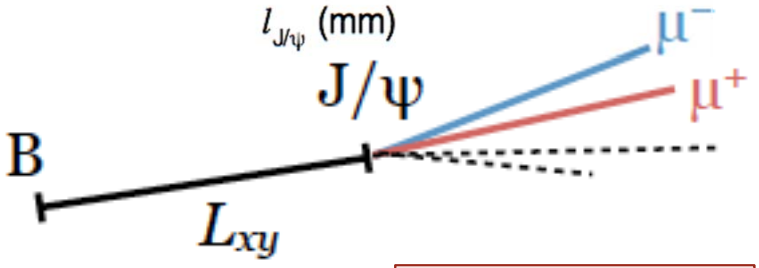
PHENIX, PRL98 (2007) 232301, also 1103.6269
SPS from Scomparin @ QM06

@LHC, B → J/ψ become significant



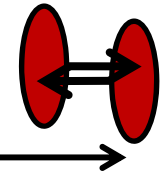




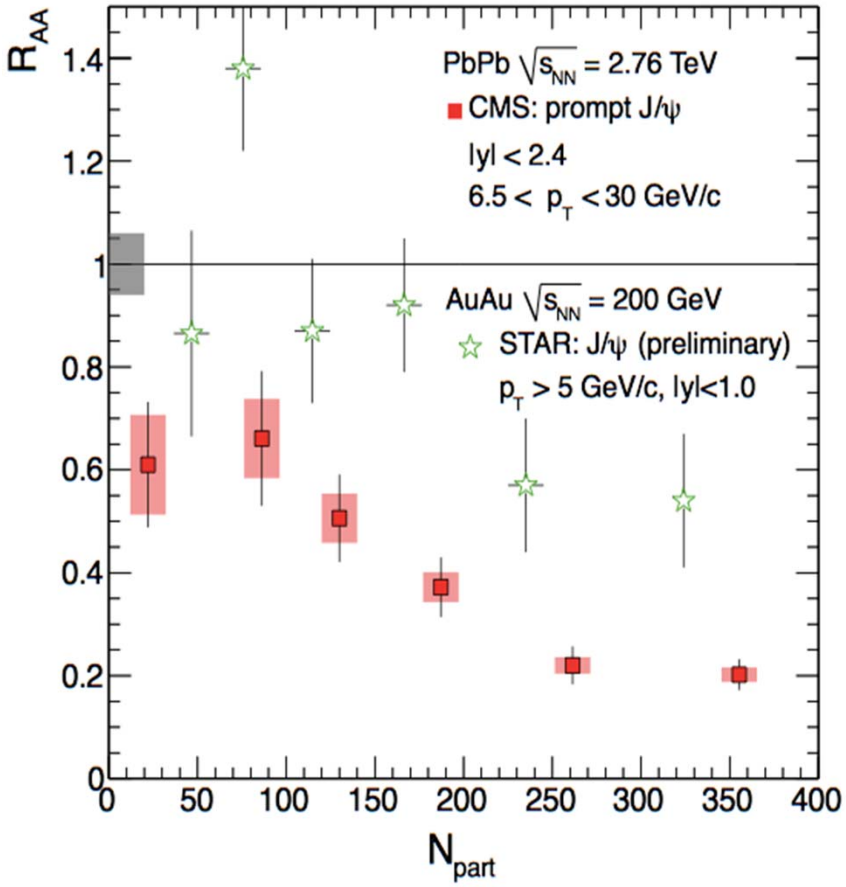


arXiv:1201.5069

Prompt J/ψ suppression



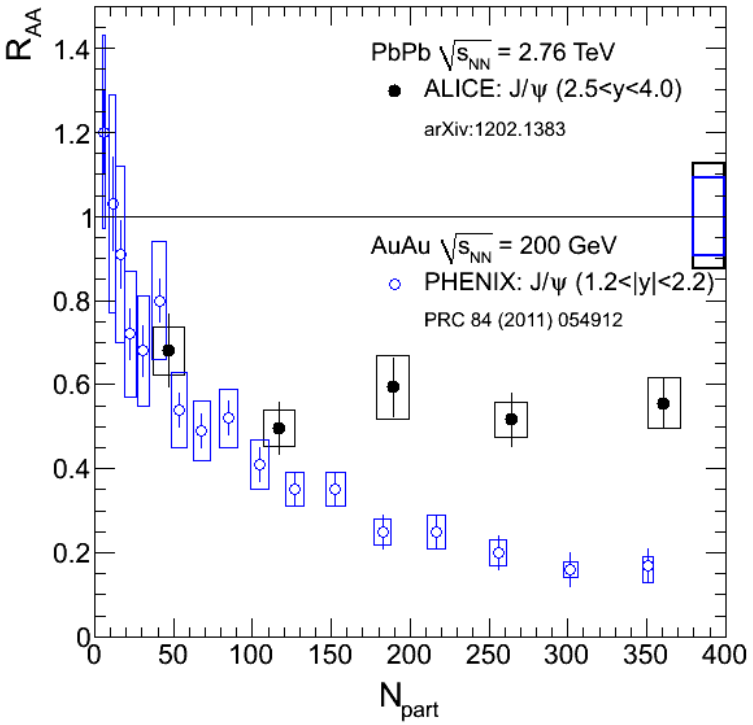
- CMS J/ψ p_T > 6.5 GeV/*c*
  - Material and B-field
- More suppression than at RHIC
  - CMS < STAR (p_T > 5 GeV/*c*)

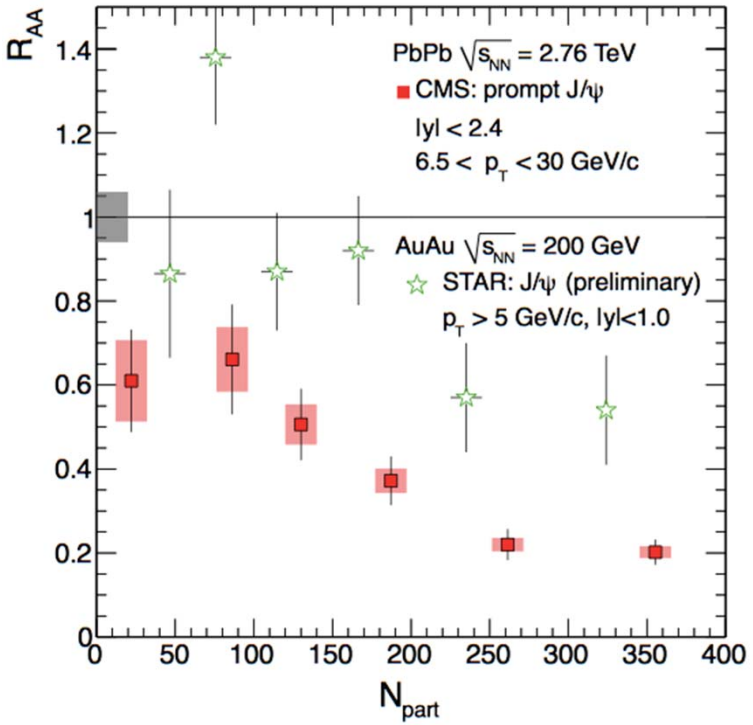


R_{AA} = 0.20 ± 0.03 ± 0.01 ± 0.01 (central)

arXiv:1201.5069

Ask Alice about lower p_T



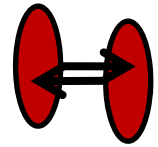


- More suppression at high p_T
- But less suppression at low p_T (and/or forward rapidity)
- Could be a case for $c\bar{c}$ recombination…

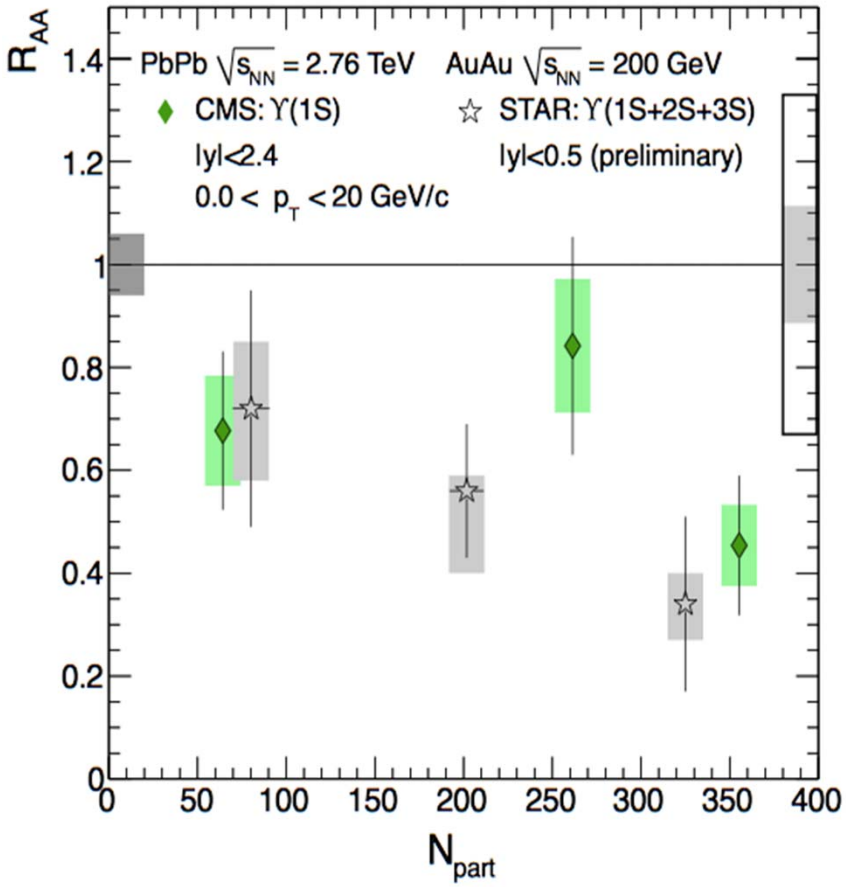
CMS, arXiv:1201.5069
ALICE, arXiv:1202.1383

arXiv:1201.5069

Upsilon(1S) suppression

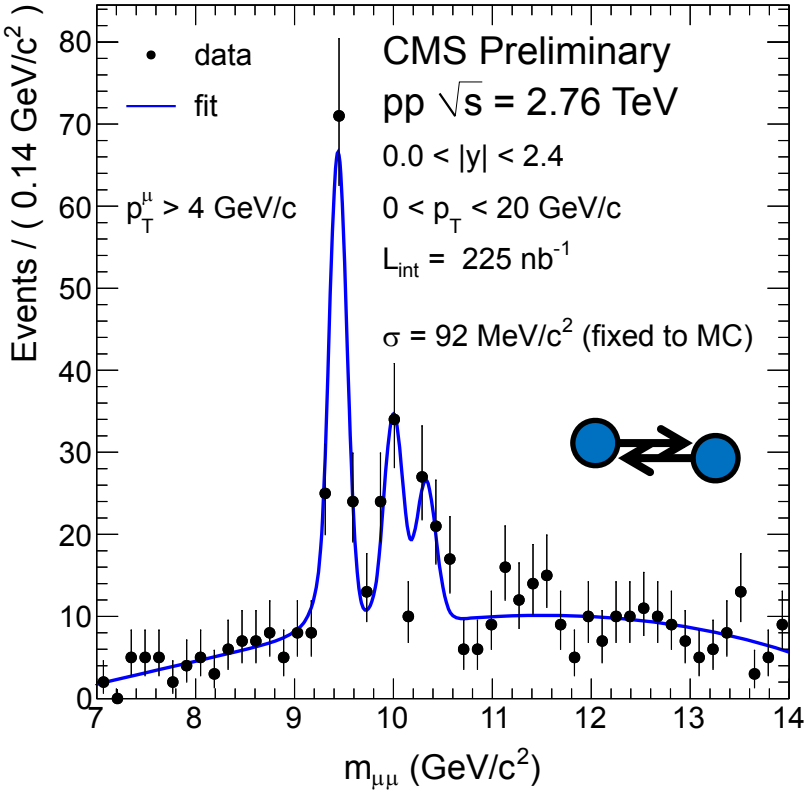


- Feed down is only from quarkonia ($\chi_B \rightarrow \Upsilon(1S)$...)
  - 50% in CDF for $p_T > 8$ GeV/c in PRL84 (2000) 2094
- Upsilon(1S) are suppressed by about 40%
- STAR measurement is for all Upsilon (1S+2S+3S)
- Compatible with a disappearance of only the excited states



$R_{AA} = 0.63 \pm 0.11 \pm 0.09 \pm 0.05$ (min.bias)

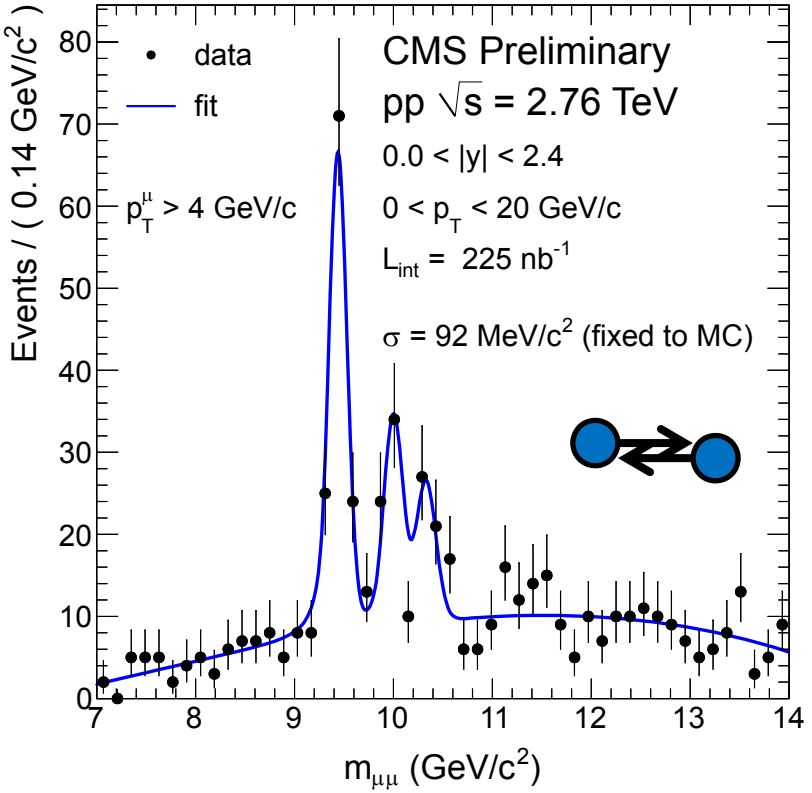
Υ excited states suppression

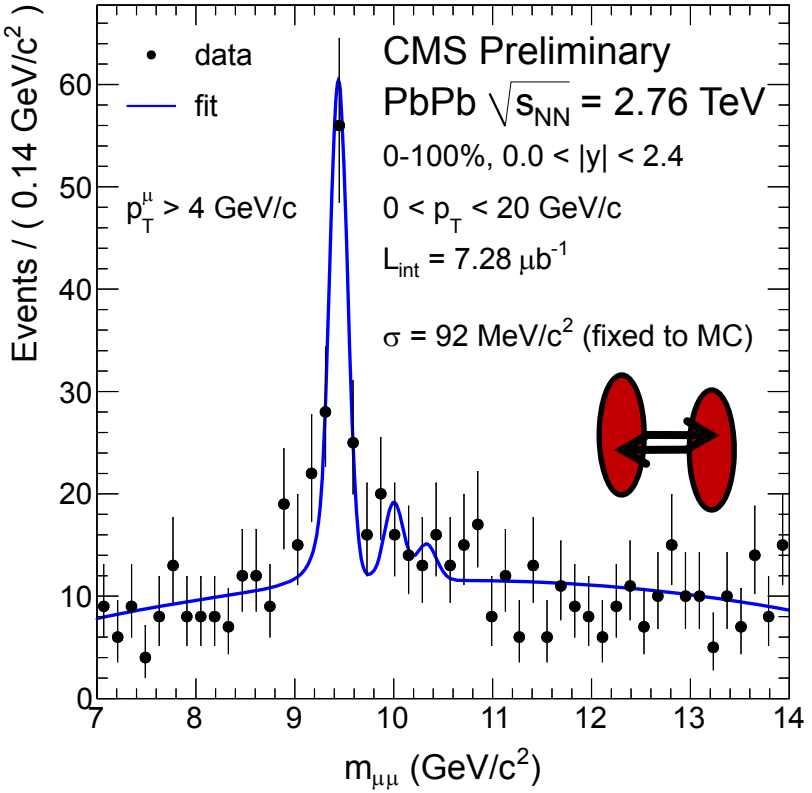


PRL107 (2011) 052302

Υ excited states suppression

in min. bias collisions





$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

PRL107 (2011) 052302

Conclusion 3: Quarkonia suppressions

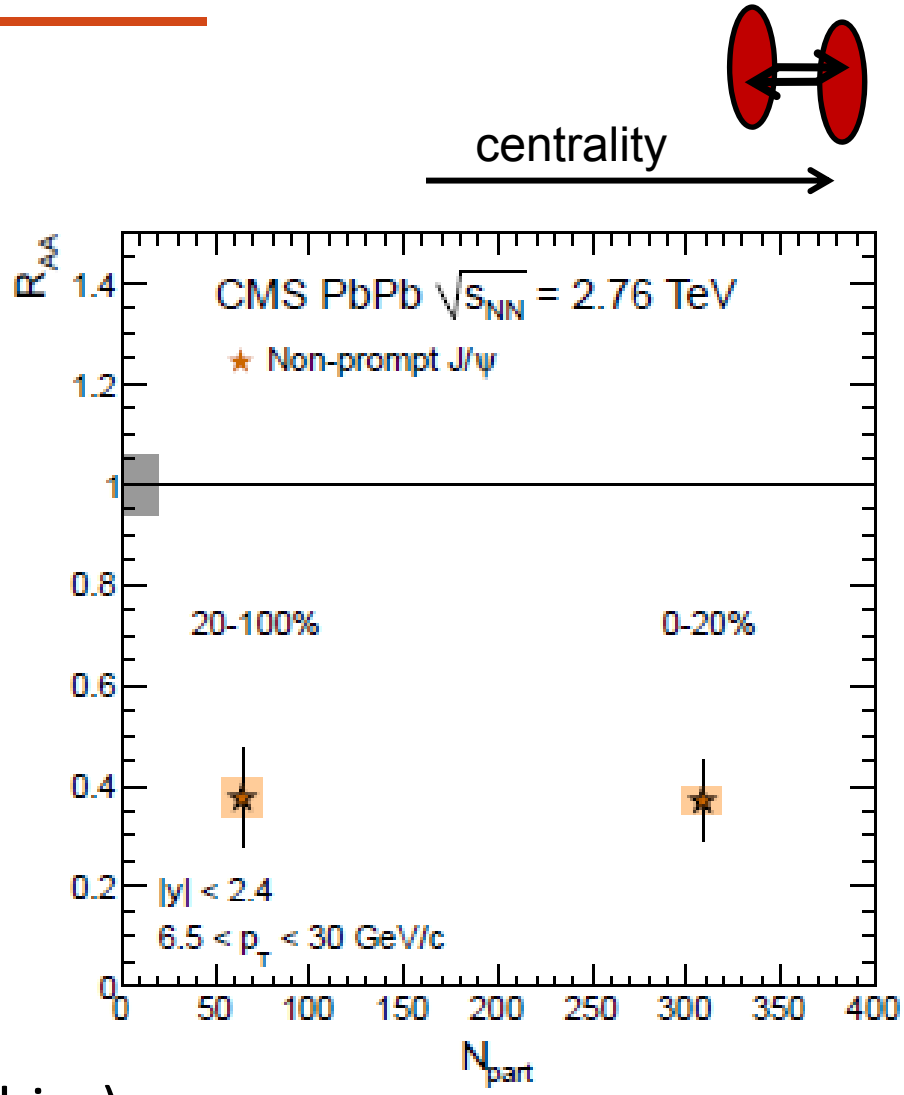
- Υ excited states are suppressed
  - First time accessible in heavy-ion collisions
  - Probability to obtain the measured double ratio (or below) if they were not suppressed is < 1 %
- Υ ground state is suppressed by about 40%
  - Excited state feed-down only?
- J/ψ are suppressed
  - More than at RHIC at high p_T (but less at low p_T)

- What about B → J/ψ ?
  - Decay outside the medium, nothing to do with quarkonia physics, but reflect the fate of the original b quark

arXiv:1201.5069

B → J/ψ suppression

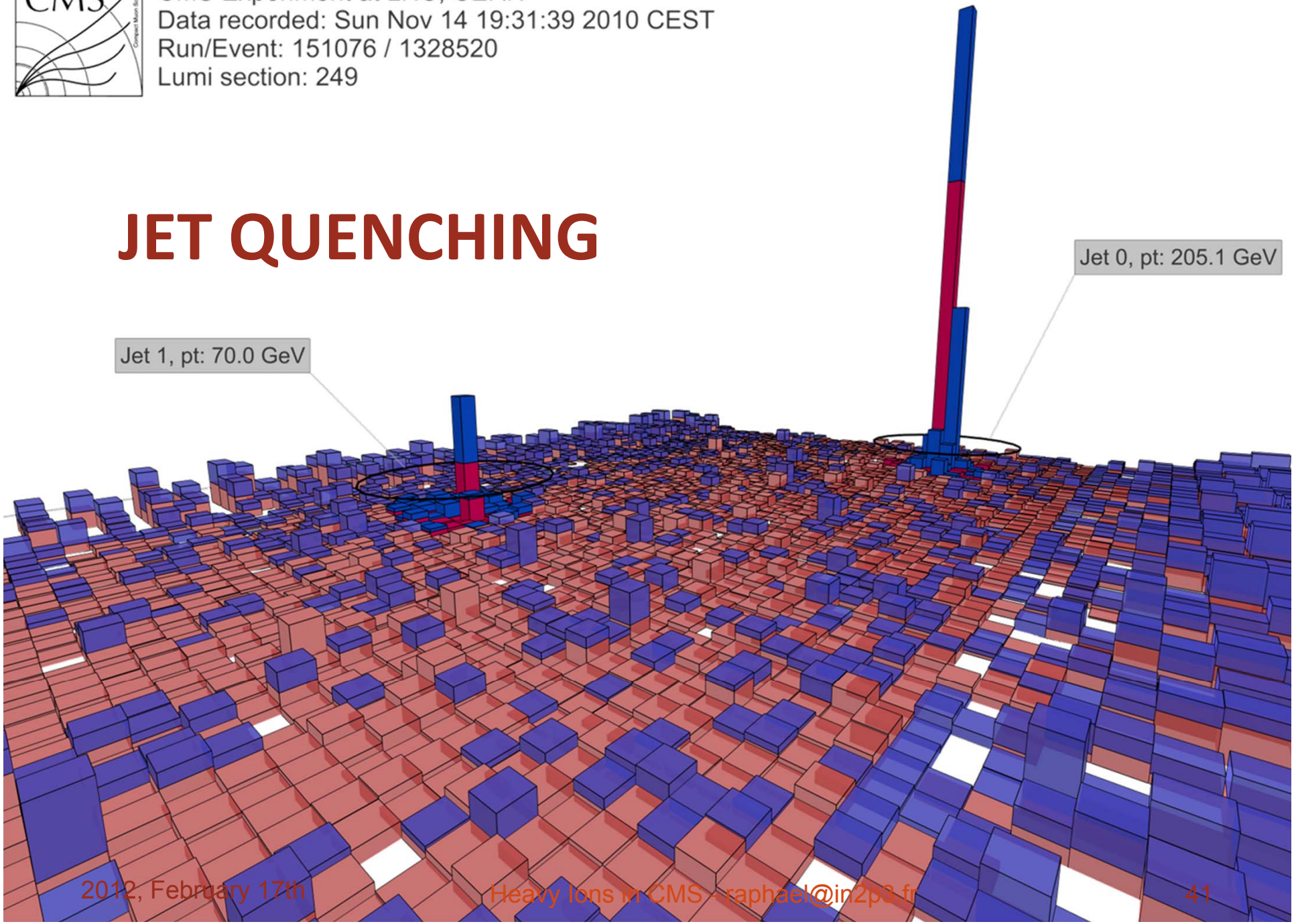
- First measurement in heavy-ion collisions
- J/ψ coming from B decay are strongly suppressed
- b-quark energy loss / quenching ?



$R_{AA} = 0.38 \pm 0.07 \pm 0.02 \pm 0.03$ (min.bias)

CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249

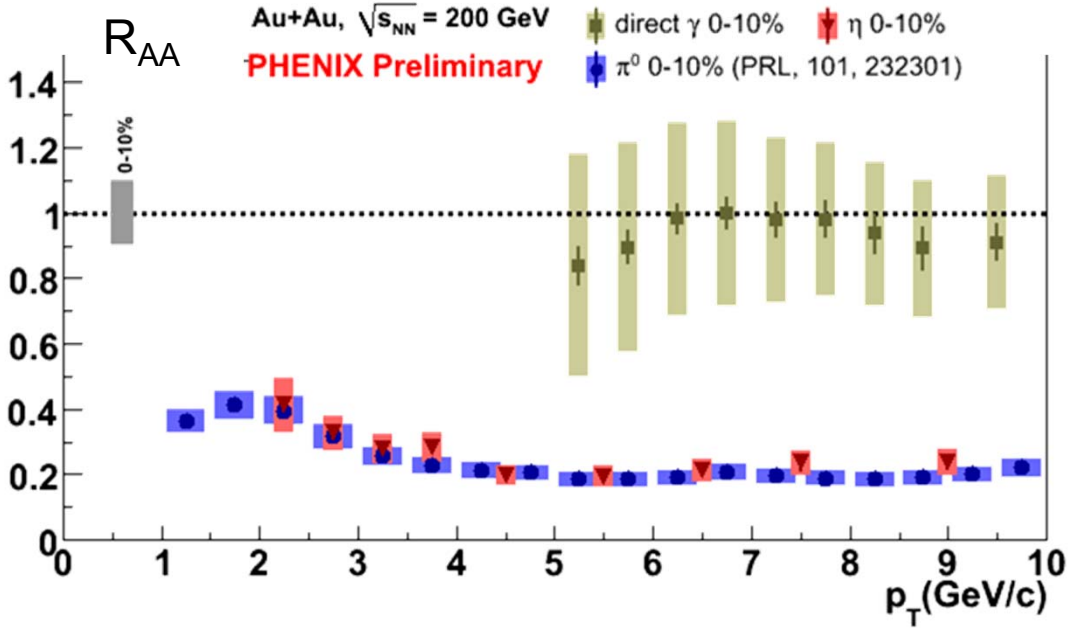
JET QUENCHING



Jet quenching

- The basic* picture @ RHIC
  - High p_T (up to 20 GeV/*c*) hadrons are suppressed
  - Reflecting quarks energy loss in the dense medium
  - Photons do not ($R_{AA} \approx 1$)

in central collisions



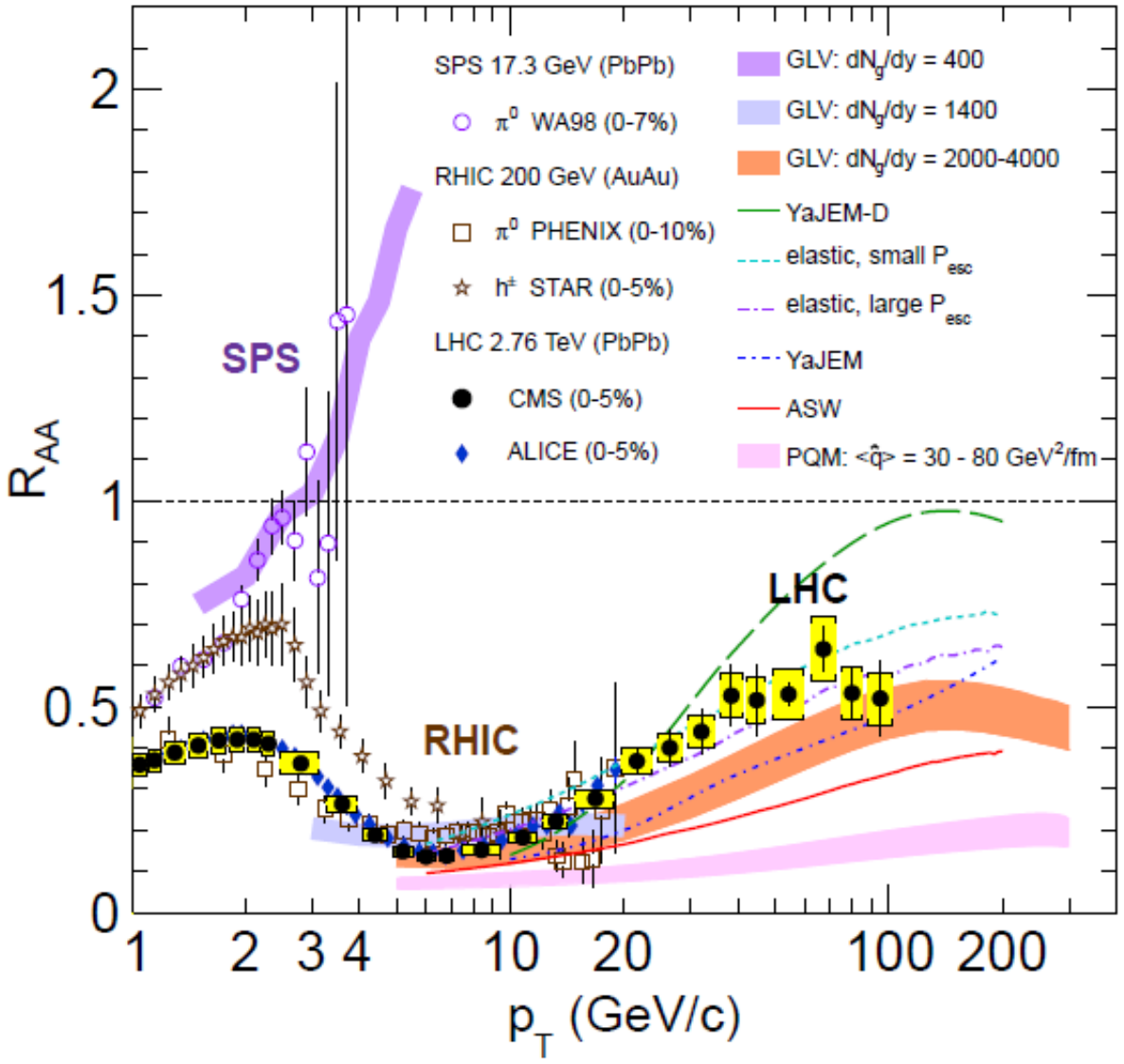
* Very extensive program with much more measurements

2011 data

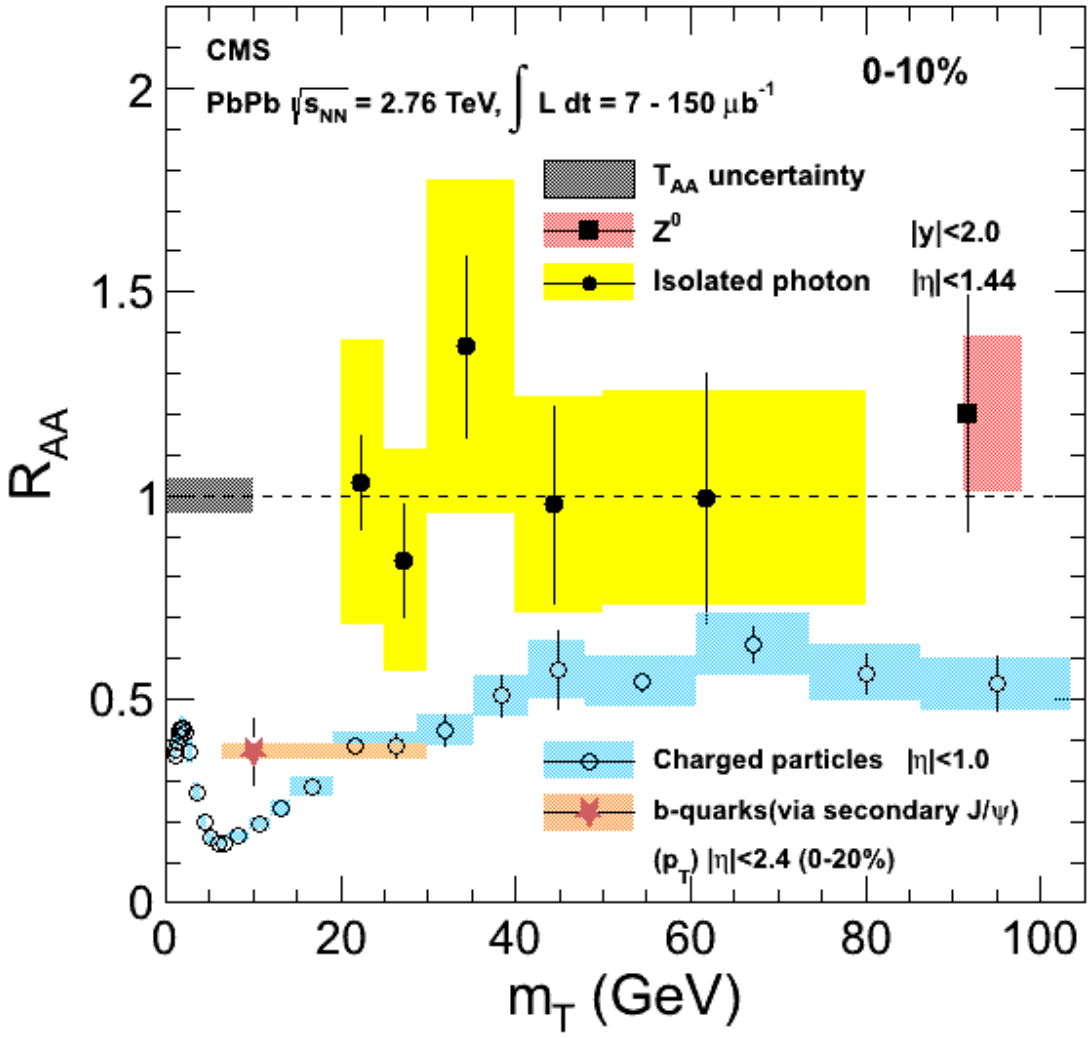
Reaching higher p_T

arXiv:1202.2554

in central collisions



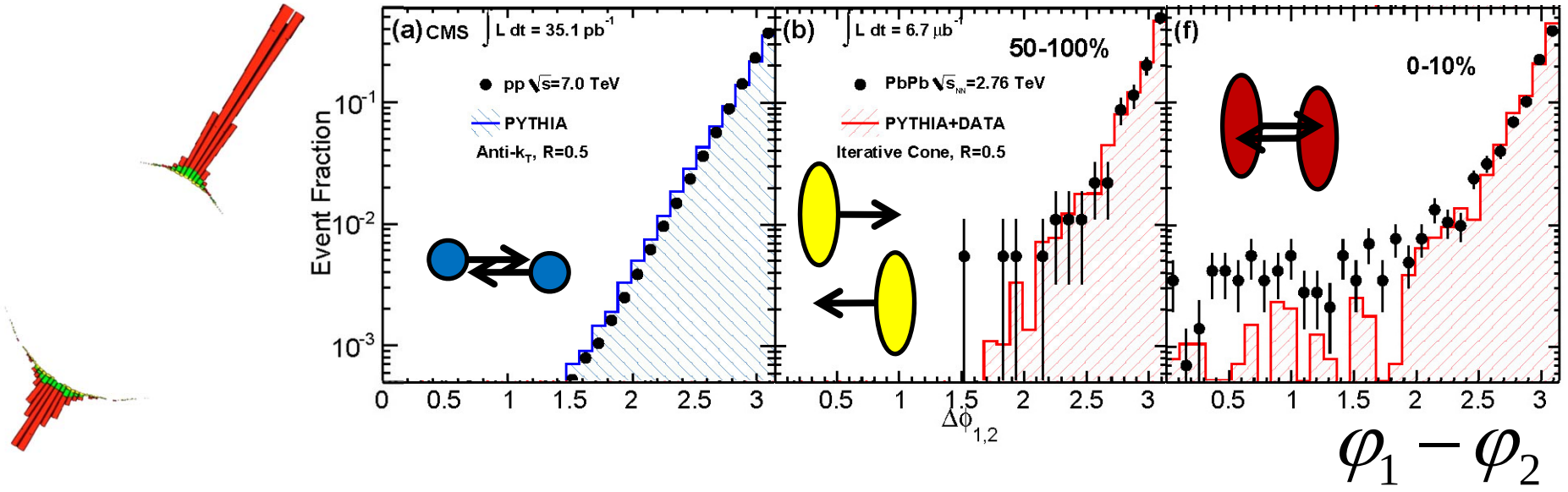
In summary…


CMS
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV, $\int$ L dt = 7 - 150 μb^{-1}
0-10%
T_{AA} uncertainty
Z^0
|y|<2.0
Isolated photon
|η|<1.44
Charged particles |η|<1.0
b-quarks(via secondary J/ψ)
(p_T) |η|<2.4 (0-20%)
R_{AA}
m_T (GeV)
0
0.5
1
1.5
2
0
20
40
60
80
100

Di-jet imbalance

PRC84 (2011) 024906

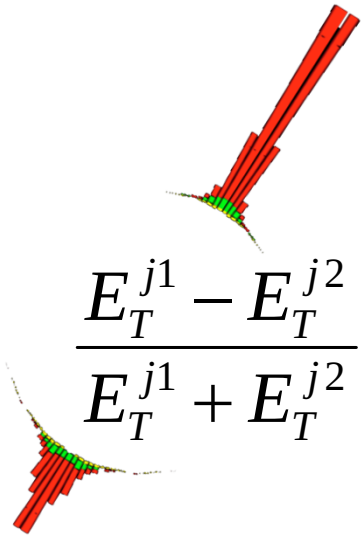
- Leading jet of $E_T^1 > 120$ GeV (trigger efficiency)
- Subleading jet $E_T^2 > 50$ GeV (above background)
- stay essentially back-to back ($\Delta\phi = \pi$) but…



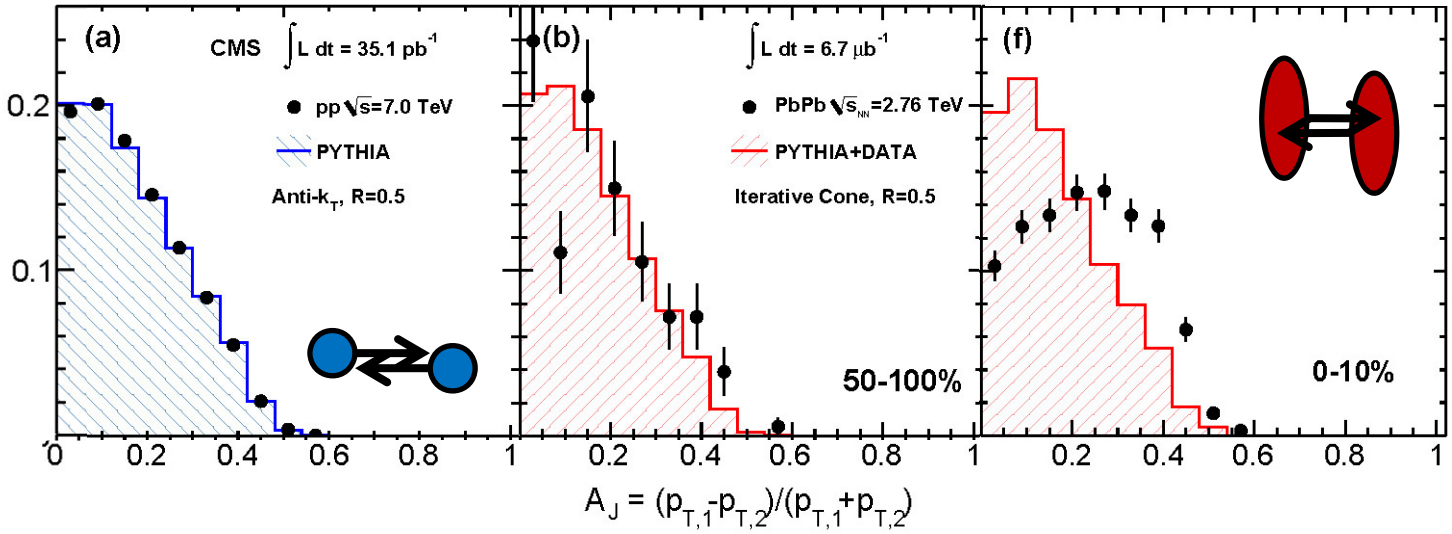
Di-jet imbalance

PRC84 (2011) 024906

- Leading jet of $E_T^1 > 120$ GeV (trigger efficiency)
- Subleading jet $E_T^2 > 50$ GeV (above background)
- stay essentially back-to back ($\Delta\phi = \pi$) but…
- highly unbalanced ($E_T^1 > E_T^2$) in central collisions

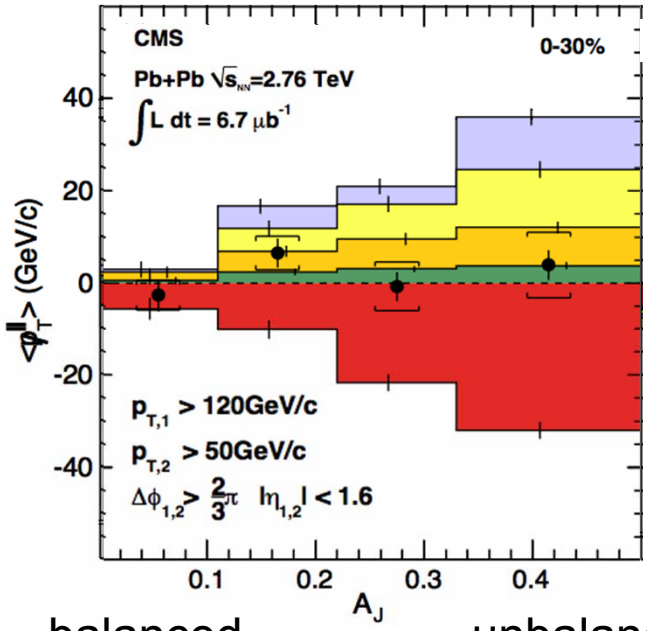


$$\frac{E_T^{j1} - E_T^{j2}}{E_T^{j1} + E_T^{j2}}$$



Finding back the missing energy…

$$\not{p}_{\mathrm{T}}^{\parallel} = \sum_{\mathrm{Tracks}} -p_{\mathrm{T}}^{\mathrm{Track}} \cos\left(\phi_{\mathrm{Track}} - \phi_{\mathrm{Leading\ Jet}}\right)$$



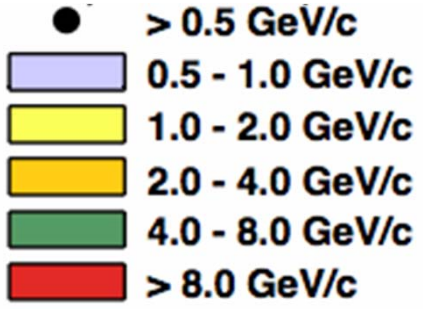
balanced dijets

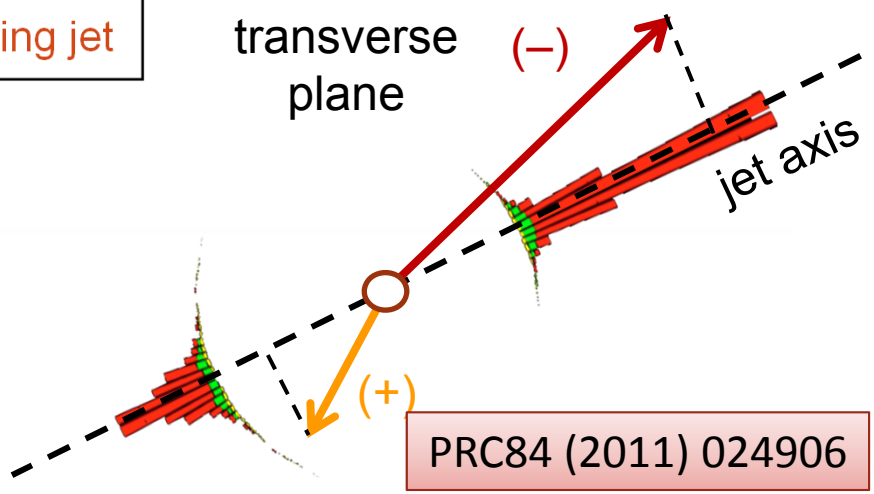
unbalanced dijets

Low p_T excess away from leading jet

Overall balance !

High p_T excess towards leading jet

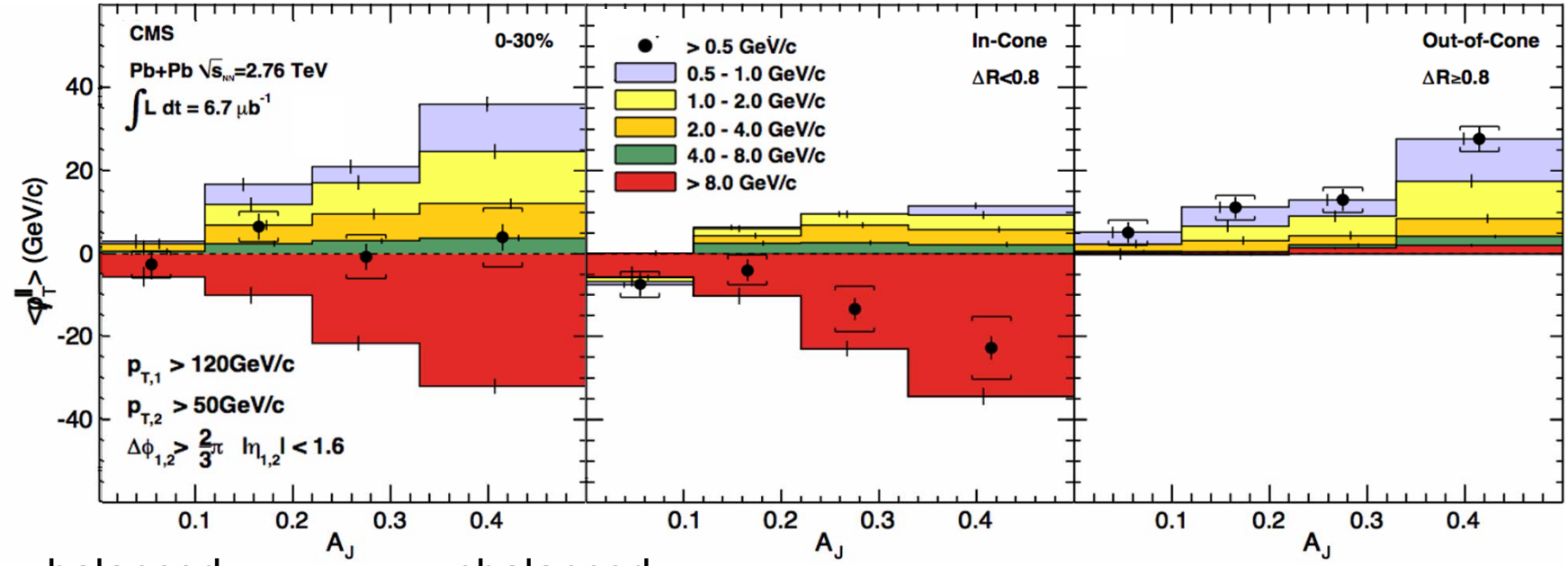




PRC84 (2011) 024906

… in low momentum, out-of-cone tracks

All particles | in cone (ΔR<0.8) | out-of-cone (ΔR>0.8)

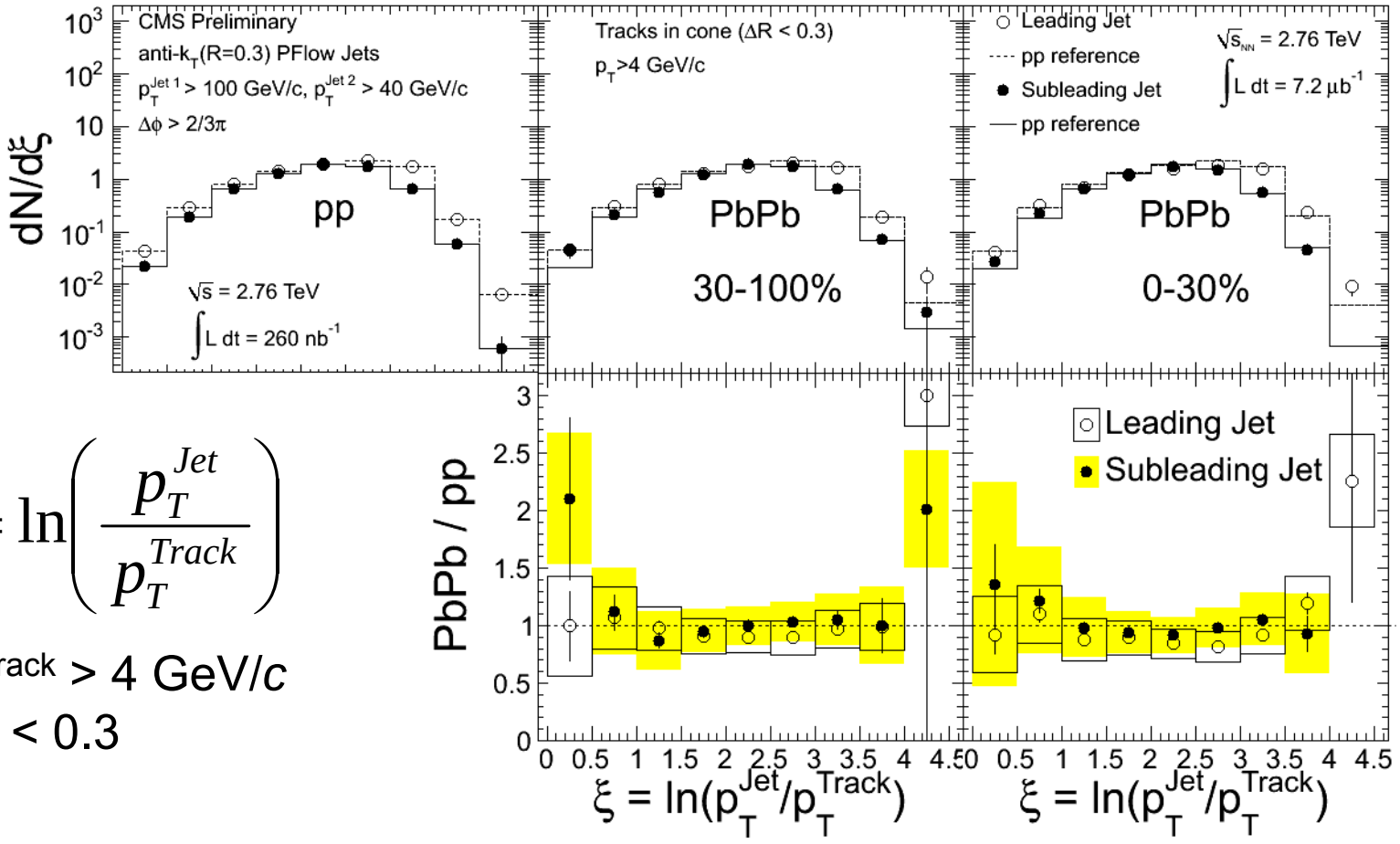


balanced dijets

unbalanced dijets

PRC84 (2011) 024906

Fragmentation functions



$$\xi = \ln\left(\frac{p_T^{Jet}}{p_T^{Track}}\right)$$

$p_T^{Track} > 4$ GeV/c
$\Delta R < 0.3$

- Surviving jets are essentially unmodified, even the subleading (quenched) one

CMS-PAS-HIN-11-004

Conclusion 4: jet quenching

- High p_T particles are still suppressed
- B-mesons are also suppressed
  - b-quark energy loss?
- Large imbalance in dijet energies
  - While angular correlation is conserved
- Energy imbalance compensated by low p_T particles over a large angle
- Hard component of jet fragmentation seems independent of the energy loss in the medium

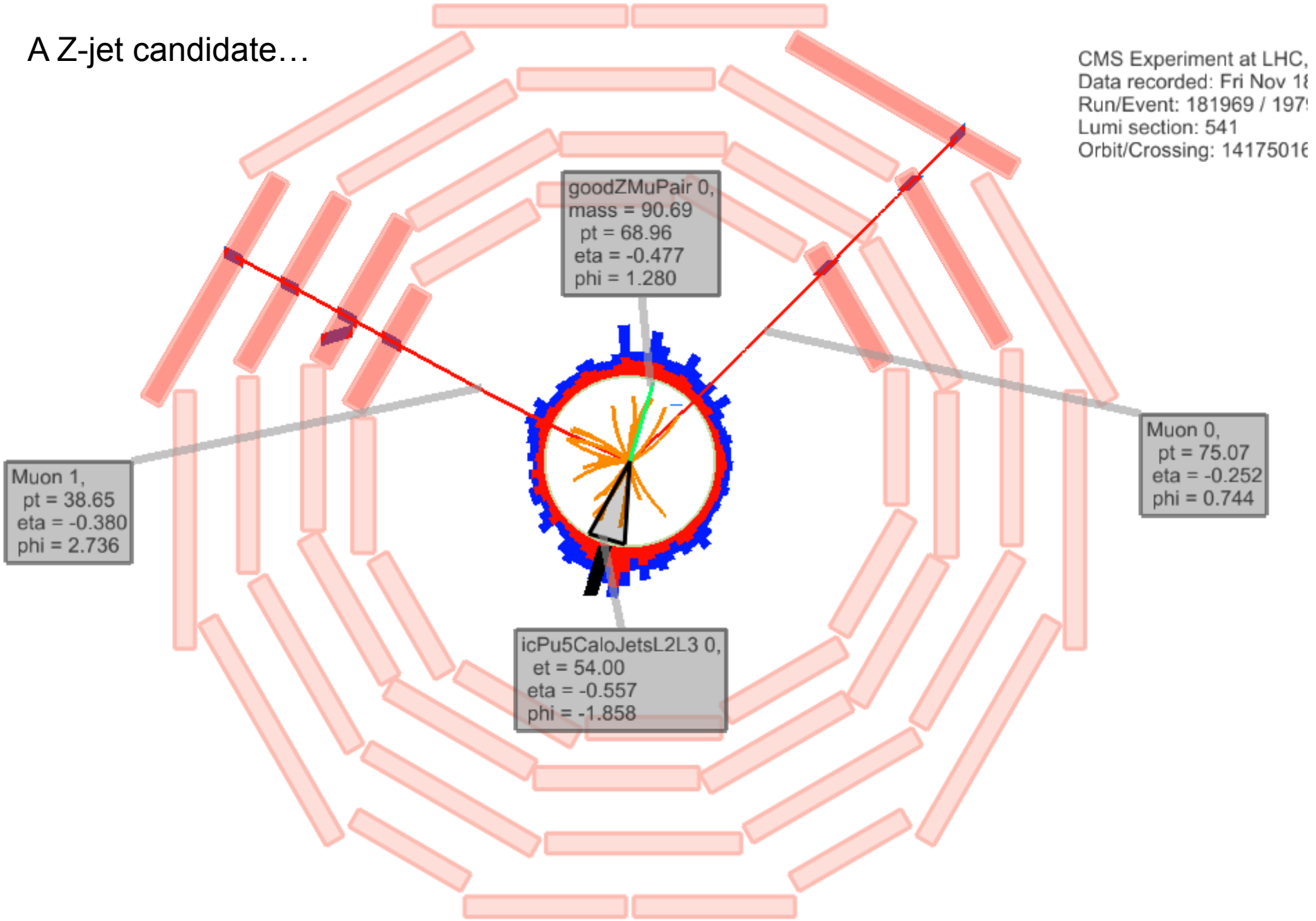
Closing remark

- Already quite a lot of results
  - 9 submitted papers on PbPb collisions
- ≈ 20 times more data on tape…
  - Already one paper with 2011 data
- And a pPb run to come to check the behavior of all the observables

- Thanks to very efficient collider, experiment, working group and people…
  - (and storing the CMS heavy-ion data at FNAL)

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN

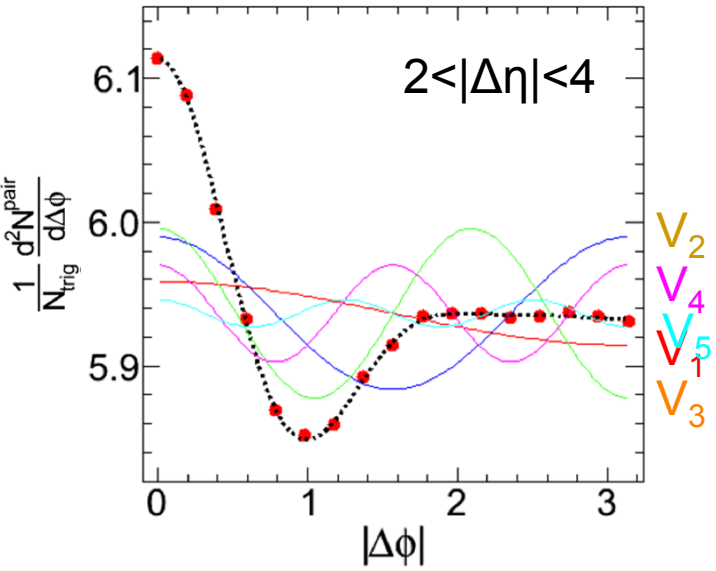
A Z-jet candidate…

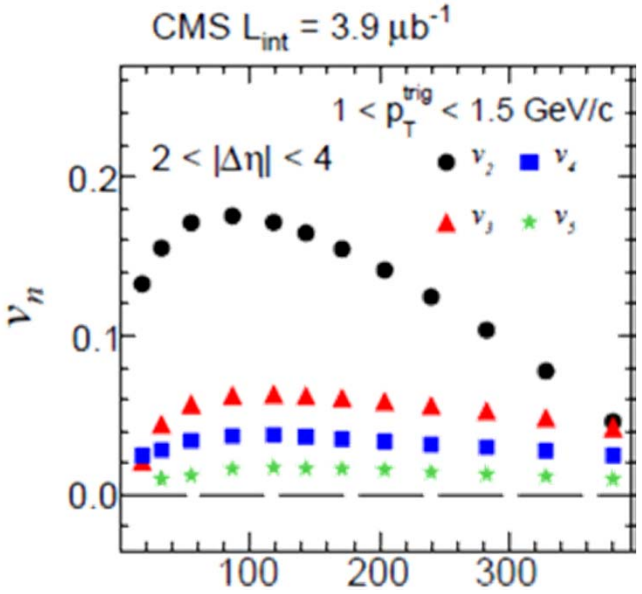


BACK UP

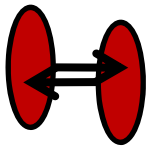
Higher harmonics?

Much more details in arXiv:1201.3158
See also HIN-11-005





1 < p_T^{trig} < 1.5 GeV
1 < p_T^{assoc} < 3 GeV



N_{part}

- In the long range region (2<|Δη|<4), dihadron harmonics shown to factorize and reflect the single particle harmonics
  - It does not on the short range (|Δη|<1),
  - nor for high p_T v_2, probably reflecting jet correlation
- The "ridge" in PbPb is well modeled by single particle harmonics and could just reflect collective motion (v_2) and overlap region fluctuations (v_n)